CRANFIELD UNIVERSITY

BARINYIMA NKOI

TECHNO-ECONOMIC STUDIES OF ENVIRONMENTALLY FRIENDLY BRAYTON CYCLES IN THE PETROCHEMICAL INDUSTRY

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ABSTRACT

Brayton cycles are open gas turbine cycles extensively used in aviation and industrial applications because of their advantageous volume and weight characteristics. With the bulk of waste exhaust heat and engine emissions associated, there is need to be mindful of environmentally-friendliness of these engine cycles, not compromising good technical performance, and economic viability.

This research considers assessment of power plants in helicopters, and aero-derivative industrial gas turbines combined-heat-and-power (ADIGT-CHP) in the petrochemical industry. Thus, it consists of two parts: part A focuses on performance analysis of helicopter gas turbines, while part B entails techno-economic and environmental risk assessment of ADIGT-CHP in the petrochemical industry. The investigation encompasses comparative assessment of simple cycle (SC) and advanced gas turbine cycle options including the component behaviours and the environmental and economic analysis of the systems. The advanced cycles considered include: recuperated (RC), intercooled (IC), intercooled-recuperated (ICR), and low pressure compressor zero-staged (LPC-ZS), cycles.

The helicopter engines are analysed and subsequently converted to small-scale ADIGT engines. Also, modelling combined-heat-and-power (CHP) performances of small-scale (SS), and large-scale (LS) ADIGT engines is implemented. More importantly, a large part of the research is devoted to developing a techno-economic model for assessing, predicting, and comparing viability of simple and advanced cycle ADIGT-CHP in the petrochemical industry in terms of net present value (NPV), internal rate of return (IRR), and simple payback period (SPBP). The techno-economic performances of the ADIGT-CHP cycles are measured against the conventional case of grid power plus on-site boiler. Besides, risk and sensitivity of NPV with respect to uncertain changes in grid electricity cost, gas fuel cost, emission cost, and electricity export tariff, are investigated. Two case studies underlie the development of the techno-economic model. One case study demonstrates the application of the model for large-scale (LS) ADIGT-CHP, and the other for small-scale (SS) ADIGT-CHP, all in the petrochemical industry. By so doing, techno-economic and environmental risk analysis framework (a multi-disciplinary preliminary design assessment tool comprising performance, emissions, economic, and risk modules) is adapted to ADIGT-CHP in the petrochemical industry, **which is the aim of this research**.

The investigation and results led to the conclusions that advanced cycle helicopter and ADIGT engines exhibit higher thermal efficiencies than simple cycle, and that savings exist in operational costs of ADIGT-CHP above the conventional case. Thus, for both SS ADIGT-CHP, and LS ADIGT-CHP cases, all ADIGT-CHP cycles are profitable than the conventional case. For LS ADIGT-CHP category, the IC ADIGT-CHP is the most profitable, whereas for SS ADIGT-CHP category, the RC ADIGT-CHP is the most profitable. **The contribution to knowledge** of this research is the development of a techno-economic model for assessing, predicting, and comparing viability of simple and advanced cycle ADIGT-CHP in the petrochemical industry in terms of NPV, SPBP, and IRR over the conventional case of grid power plus on-site boiler. A second contribution is the derivation of simple and advanced cycle small-scale ADIGT and ADIGT-CHP from helicopter engines.

The developed techno-economic model exhibits some capabilities which are improvements on some other models that were reviewed. It is able to account for cost of total emissions to include NO_x, CO, CO_2, and H_2O_{vapour}; compare viability of ADIGT-CHP cycle options with one another as well as with conventional case of grid power plus on-site boiler to determine cost savings of using CHP; considers NPV risk analysis using Latin Hypercube sampling technique which gives a better spread of sampled inputs from frequency distributions than Monte Carlo sampling method. On the other hand, previous models account for emission cost of only CO_2, and estimate savings of one GT-CHP cycle with respect to conventional case only.

Keywords:

Aero-derivative gas turbines, combined-heat-and-power, gas turbine performance, Techno-economic analysis, risk assessment, net present value

DEDICATION

I dedicate this research work to the memory of my beloved father Pa Isaiah Gonwa Nkoi.

LIST OF PUBLICATIONS

Nkoi B., Pilidis P., and Nikolaidis T.(2013) 'Performance assessment of simple and modified cycle turboshaft gas turbines', *Journal of Propulsion and Power Research*. Elsevier. 2013; 2(2): 96 – 106.

Nkoi B., Pilidis P., and Nikolaidis T.(2013) 'Performance of small-scale aero-derivative industrial gas turbines derived from helicopter engines', *Journal of Propulsion and Power Research*. Elsevier. 2013; 2(4): 243 – 253.

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LIST OF ABBREVIATIONS

Abbreviation	Description
ACARE	Advisory council for Aeronautics Research in Europe
ADIGT	Aero-derivative industrial gas turbines
ADIGT-CHP	Aero-derivative industrial gas turbines combined-heat-and-power
CC	Combined-cycle
CCU	Combined-cycle unit
CHP	Combined-heat-and-power
CO	Carbon mono-oxide
CO_2	Carbon dioxide
DLE	Dry low emission
DLN	Dry low NO_x
DP	Design-point
EC	Eurocopter
GE	General Electric
GT	Gas turbine
H_2O	Steam, water vapour
HEPHAESTUS	GT engine emissions prediction code
Heli	Helicopter
HP	High pressure
HPC	High pressure compressor
HPT	High pressure turbine
Ib	Pounds
IC	Intercooled cycle
ICR	Intercooled-recuperated cycle
Inter	Intercooler
IPT	Intermediate pressure turbine
IRR	Internal rate of return
ISA	International standard atmosphere
ISA Dev	International standard atmosphere deviation
JTI	Joint Technology Initiative
K	Degree Kelvin
kg	Kilo-gram
kW	Kilo-Watts

kJ	Kilo-Joule
LNG	Liquified natural gas
LP	Low pressure
LPC	Low pressure compressor
LPC-ZS	Low pressure compressor zero-staged
LPT	Low pressure turbine
LS	Large-scale
LS-ADIGT	Large-scale aero-derivative industrial gas turbines
LS-ADIGT-CHP	Large-scale aero-derivative industrial gas turbines combined-heat –and-power
LS1-ADIGT	Large-scale-class-1 aero-derivative industrial gas turbines
LS2-ADIGT	Large-scale-class-2 aero-derivative industrial gas turbines
LSRCP	Large-scale refinery and chemical plant
LSRCP-CHP	Large-scale refinery and chemical plant combined-heat-and-power
MEA	Manx Electricity Authority
MTBF	Mean time between failure
MTTR	Mean time to repair
MW	Mega-Watts
m^2	Square meter
N	Newton
N/A	Not available
NASA	National Aeronautics and Space Administration
NO_x	Oxides of nitrogen
NPV	Net present value
OD	Off-design point
OEM	Original equipment manufacturer
OPR	Overall pressure ratio
PR	Pressure ratio
Regen	Regenerator
RC	Recuperated
RoI	Return on investment
s	Second
SAC	Standard annular combustor
SLS	Sea level static
SPBP	Simple payback period

SS	Small-scale
SS-ADIGT	Small-scale aero-derivative industrial gas turbines
SS-ADIGT-CHP	Small-scale aero-derivative industrial gas turbines combined-heat-and-power
SSRP	Small-scale refinery plant
SSRP-CHP	Small-scale refinery plant combined-heat-and-power
ST	Steam turbine
TERA	Techno-economic and environmental risk analysis
TET	Turbine entry temperature
TRL	Technology readiness level
TSTF	Three spool turbo fan
TTTR	Total time to repair
TURBOMATCH	Gas turbine engine performance model
UHC	Unburnt hydrocarbon
USAF	United State Air Force
ZS	Zero-stage

Symbol	Description	Unit
A_{Lt}	equal yearly payments of principal and interest for repayment of loan	£
c	Specific heat	kJ/kg
C	Investment capital cost	£
C_{Bh}	Cost of boiler heat	£
C_e	Avoided cost of electricity by CHP	£
C_{emtx}	Emission tax	£
C_f	Cost of fuel for CHP	£
C_g	Investment grant	£
C_{Ge}	Cost of Grid electricity	£
C_h	Avoided cost of heat by CHP	£
C_{Lr}	Equal annual loan repayment	£
$C_{o/m}$	Cost of operation and maintenance of plant minus fuel cost	£
c_p	Specific heat at constant pressure	kJ/kg
c_{pa}	specific heat at constant pressure of air	kJ/kg
CW	Compression work	kJ
d	Constant market discount rate	%
d_t	Variable market discount rate in time period t	%

EW	Expansion work	kJ
F_0	Present worth of investment capital cost	£
F_t	Annual net cash flow for year t	£
f_t	Annual operation savings	£
FF	Fuel flow in combustor	Kg/s
h	Specific enthalpy	kJ/kg
h_a	Water specific enthalpy at economiser inlet	kJ/kg
h_c	Saturated water specific enthalpy at evaporator inlet	kJ/kg
h_d	Saturated steam specific enthalpy at evaporator exit	kJ/kg
h_e	Superheated steam specific enthalpy	kJ/kg
L	Loan	£
LHV	Low heating value of fuel	kJ/kg
$\dot{m}_f$	Fuel mass flow in combustor	Kg/s
N	Life of CHP project investment	years
P	Pressure	N/m^2
P_E	Electrical power	kWe
P_T	Gas turbine power	kW
q	Heat flow	kW
q_{in}	Heat flow in	kW
q_{out}	Heat flow out	kW
Q_{4x}	Total heat transfer in superheater and evaporator	kW
Q_{comb}	Combustor heat input	kW
Q_{econ}	Economiser duty	kW
Q_{evap}	Evaporator duty	kW
Q_{super}	Superheater duty	kW
Q_{HRSG}	HRSG duty	kW
R_e	Revenue from excess electricity from sold from CHP	£
r	Interest rate on loan	%
r_T	Tax rate	%
S	Entropy	kJ/kgK
SFC	Specific fuel consumption	kg/MWs
SV_N	Salvage value of the investment at the end of the economic life N	£
T	Temperature	K
T_a	Water temperature at HRSG economiser inlet	K

T_b	Temperature at HRSG economiser exit	K
T_c	HRSG steam saturation temperature	K
T_e	HRSG superheated steam temperature	K
T_t	Taxable income in year t, due to CHP	£
T_x	Exhaust gas temperature at pinch point of HRSG	K
T_y	Exhaust gas temperature at HRSG evaporator exit	K
T_4	Gas turbine exhaust temperature to HRSG	K
ΔT_{4y}	Gas temperature drop in superheater	K
ΔT_{x1}	Gas temperature drop in the economiser	K
ε	Heat exchanger effectiveness	%
η	Efficiency	%
η_{th}	Thermal efficiency	%
η_c	Compressor isentropic efficiency	%
η_T	Turbine isentropic efficiency	%
η_1	First law CHP efficiency	%
η_2	Second law CHP efficiency	%
η_E	Electrical generator efficiency	%
π	Pressure ratio	a constant
Υ	Ratio of specific heats	a constant
w_g	Exhaust gas mass flow	Kg/s
W_{net}	Net work	kJ
w_s	Steam mass flow	Kg/s
$\dot{W}_E$	Electrical energy rate	kW
$\dot{W}_{ST}$	Steam energy rate	kW
σ	Standard deviation	
$\sum$	Summation	
μ	Mean of statistical distribution	
%	Percentage	
ΔS_f	Entropy released by fuel combustion	kJ/kgK
Δh_f	Low heating value of fuel	kJ/kg

1 INTRODUCTION

1.1 Background and justification of study

This research considers assessment of power plants in helicopters, and aero-derivative industrial gas turbines combined-heat-and-power (ADIGT-CHP) in the petrochemical industry. Thus, the research comprises two parts: part A focuses on performance analysis of civil helicopter gas turbines, while part B deals with techno-economic and environmental risk analysis of ADIGT-CHP in the petrochemical industry. The investigation encompasses comparative assessment of simple and advanced gas turbine cycle options including the component behaviours and the environmental and economic analysis of the systems. Techno-economic and environmental risk analysis (TERA) framework is adapted, and part of it developed. This forms a multi-disciplinary preliminary design assessment tool comprising several modules, namely: engine performance, emissions, economic, and risk modules.

Fundamentally, Brayton cycle is the thermodynamic cycle on the principles of which gas turbine power plants operate. It is commonly referred to as the standard open gas turbine cycle (Hart, 2005; Giampaolo, 2003). Brayton cycles are extensively used in civil aviation and petrochemical industry because of their advantageous volume and weight characteristics. Basically, these cycles are used as prime movers in mechanical drive of rotating equipment, pumping of fluids, electric power generation, and industrial process or domestic heat generation in combined-heat-and-power applications (Soares, 2008). Gas turbine is the unique heat engine (also a fluid machine) that has over the years brought thrust and power generation to fore, and unarguably one of the most important developments of the 20th century that has changed human lives in many ways (Saravanamuttoo et al, 2009).

A Brayton cycle is deemed environmentally friendly if energy losses in form of heat to the environment is reduced, noise is reduced, fuel efficiency is enhanced, and also engine emissions lessened. The achievement of any one or all of these criteria is satisfactory for an environmentally friendly cycle. These energy efficiency criteria in the petrochemical industry are of critical importance, where power and steam generation and utilisation are regularly in very high demand. The supposedly wasted heat in the exhaust of gas turbine engines could be harnessed for very useful purposes like generating steam in order to reduce heating up the environment, reduce global warming, and improve fuel efficiency. This utilisation of gas turbine exhaust waste heat could be achieved by the application of combined-heat-and-power (CHP) concept where both power and steam are simultaneously generated from a single fuel source.

Therefore, combined-heat-and-power generation using aero-derivative industrial gas turbines (ADIGT) is identified and considered as one cycle that would achieve most of the criteria of environmentally friendly Brayton cycles. However, selection of appropriate and viable cycle option for this purpose poses serious decision-making concern. Hence, in order to aid good choice of ADIGT-CHP cycle option in the petrochemical industry, TERA framework is adapted in this research to assess, predict, and compare performances of ADIGT-CHP cycle options.

1.1.1 Research scope

With reference to review of previous research presented in section 2.1, the **research gaps** identified to be addressed in this research are outlined below.

- Regarding part A of this research which is about helicopter engines performance assessment, investigations have been carried out by others on advancement of the helicopter turbo-shaft engine in the area of improving the power output, the specific fuel consumption, and thermal efficiency. This has been done for instance by methods of increasing the turbine entry temperature, and zero staging the LP compressor (Vickers, 1995).

  This trend of improving thermal efficiency by preliminary design modification is extended in this research by methods of intercooled-recuperation of helicopter gas turbines. This research goes further to consider the conversion of helicopter engines to small-scale ADIGTs, and investigate their performances and economic viability in CHP application in the petrochemical industry.

- Regarding part B of this research, the use of TERA has been previously demonstrated in jet engine modeling and management to optimize the thrust and weight (Ogaji et al, 2007). Also, research has been carried out on technical risk analysis of gas turbines for natural gas liquefaction, in which machine downtime was identified as an empirical measure of technical risk (Khan et al, 2011).
  In this regard, this research extends adaptation of TERA framework to ADIGT-CHP in the petrochemical industry, whereby a techno-economic model is formulated and developed as a preliminary design and decision tool. This model would estimate the net present value (NPV), internal rate of return (IRR), and simple pay-back period (SPBP) of ADIGT-CHP putting into account capital cost, total emissions cost, fuel cost, O&M cost, etc. Risk and sensitivity of NPV would also be analysed, all aiming at predicting and comparing viability of ADIGT-CHP cycle options in the petrochemical industry. The TERA philosophy as adapted in this research is shown in Figure 1-1.

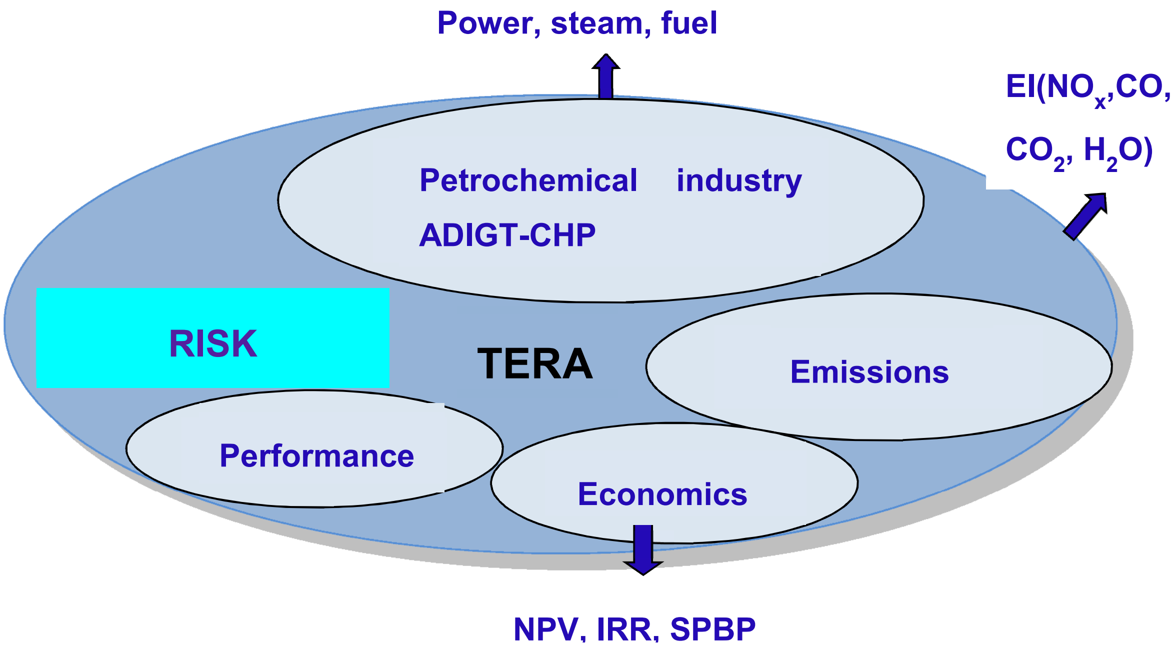

Figure 1-1 TERA philosophy for ADIGT-CHP in the petrochemical industry

1.1.2 Technical requirement

Gas turbine user requirements have, over the years, necessitated technological advancement in engine performance, and comprehensive researches are being conducted to achieve this. Current researches are significant in engine advancements in the areas of high temperature small turbine units, cost effective new technologies, engine component lifing, environmental friendliness, among others (Paramour and Sapsard, 1981).

Improvement of thermal efficiency for industrial and aero gas turbines is of paramount importance to the overall performance of the engines. Thermal efficiency is an indicator of the virtue of the thermodynamic cycle, showing the extent to which the burnt fuel energy increases the kinetic energy of the expanding gases. Increase in thermal efficiency depends on certain factors including:

- Changes in some engine cycle parameters, such as overall pressure ratio (OPR), and turbine entry temperature (TET).
- Cutting-edge technology of engine components like methods of cooling, efficiencies of components, ducts pressure losses, and
- Introduction of different overall thermodynamic cycle, for example, use of unconventional components like intercoolers and regenerators or recuperators (Pilidis and Palmer, 2010; Bhargava et al, 2010).

1.1.3 Environmental requirement

Waste heat from exhausts of gas turbines is a huge and formidable source of global warming, and energy loss to the environment. Also, emissions from gas turbine engines in both aviation and industrial applications have contributed immensely to degradation of local air quality in airport vicinities, and to greenhouse effect and global warming the world over. Fuel efficiency in terms of fuel burn and fuel consumption is a direct measure of engine emissions like CO_2, CO, UHC, and NO_x.

There is the need to continuously improve on reducing the amount of waste heat from exhaust gas and emissions in order to make gas turbine operation environmentally-friendly. This has resulted in more proactive environmental concern for all, and relevant authorities have instituted measures such as sponsoring appropriate researches to find ways of mitigating this inflicted environmental degradation. For instance the Advisory Council for Aeronautics Research in Europe (ACARE) has defined some targets for 2020 and 2050 among which is reducing CO_2 emission by 50%.

Eventually, fuel efficiency of civil aero-engines has constantly improved over some years now. This has been due to improved thermal and propulsive efficiencies occasioned by some engine technology advancement such as increased overall pressure ratio, high by-pass ratio, better cooling and materials, etc. More so, emissions of CO, CO_2, and UBH have markedly reduced whereas NO_x emission has relatively maintained steady level (ACARE, 2012). Also, Clean Sky Joint Technology Initiative (JTI) - European Union collaboration, has set goals aiming at reducing fuel consumption, CO_2 emission by 75%, NO_x by 90% and sensed external noise by 65% (Clean Sky, 2013; Kurt et al, 2009).

1.1.4 Economic requirement

The technical and environmental aspects of gas turbine engine design and operation cannot be discussed and handled without involving the economic case associated with developing and launching a new product, or modifying an existing one. Performance and economic viability of gas turbine are inseparable. This is because performance is made up of shaft power, or thrust, produced for any given diameter of engine, fuel flow rate, life, engine emissions, weight, and unit cost, sold by a gas turbine manufacturer and bought by a user. If an engine with bad performance is designed, the sellers will definitely strife hard to sell and most likely make losses. Likewise, a user who buys a poorly designed engine will lose income.

Fuel burn, engine component life, maintenance requirements (overhaul and repair costs), engine weight and initial cost, etc., are all anchored on the performance parameters; fuel burn often being the dominant item. For instance, fuel cost is about 85% of the operating costs in base load power generation, and items related to engine performance represent 35% of the operating costs of a Boeing 737 (Walsh and Fletcher, 2004).

1.2 Research question

A gas turbine asset manager or product development engineer who is faced with the challenge of decision making would need to ask and seek answers to some pertinent questions. A question that would need to be asked and answered is how one would make the choice of ADIGT-CHP cycle option in the petrochemical industry that would produce good return on investment (RoI), considering economic benefits. This research to provide a framework to aiding such decision of choice of ADIGT-CHP cycle options in the petrochemical industry.

1.3 Aim of research

The aim of this research is to adapt techno-economic and environmental risk analysis (TERA) framework for aero-derivative industrial gas turbines combined-heat-and-power (ADIGT-CHP) in the petrochemical industry.

1.4 Research objectives

To achieve the aim of this research, the following objectives are set:

- To analyse technical performances of simple and advanced cycle helicopter engines.
- To convert helicopter engines to small-scale ADIGT (SS-ADIGT).
- To analyse technical performances, and estimate engine emissions of small and large scale ADIGT.
- To identify CHP as environmentally friendly Brayton cycle in the petrochemical industry.
- To analyse technical performances of small and large scale ADIGT-CHP cycles.
- To carry out techno-economic and risk analysis of simple and advanced cycle ADIGT-CHP in the petrochemical industry.
- To develop a techno-economic model to assess the viability of various ADIGT-CHP cycle options in the petrochemical industry.
- To provide a multi-disciplinary framework for comparing investments in different cycle options of ADIGT plant equipment for application in CHP generation in the petrochemical industry with respect to conventional case.

1.5 Contribution to knowledge

The contribution to knowledge of this research is the development of a model for assessing, predicting, and comparing the techno-economic viability of simple and advanced cycle ADIGT-CHP in the petrochemical industry over the conventional case of grid power plus on-site boiler. A second contribution is the derivation of simple and advanced cycle small-scale ADIGT and ADIGT-CHP from helicopter gas turbine engines.

1.6 Research methodology overview

This research consists of two parts: part A focuses on the performance analysis of helicopter gas turbines that would subsequently be converted to SS-ADIGT, and the following methods and approach are adopted:

- Simulation of: a simple cycle (SC) two-spool turboshaft gas turbine inspired by Turbomecca Makila 2A engine core; LP compressor zero staged (LPC-ZS), Recuperated (RC), and Intercooled/recuperated (ICR), engines of same core and power rating. This is implemented by the method of applying TURBOMATCH code, description of which is given in section 2.8. Detail methodology is presented in chapter 3.
- Verifying performance parameters of the base engine modelled.
- Establishing performances of the helicopter engine models at design and off - design conditions.
- Comparing performances of the various helicopter engine cycles.

Part B deals with the techno-economic and environmental risk assessment of ADIGT-CHP application in the petrochemical industry, and the following methods and approach are followed:

- The helicopter engine models analysed in part A (named above) are converted to form representative small-scale (SS) ADIGT by modification of key parameters. This is implemented by simulation using TURBOMATCH code. In addition, design models of two-spool, and three-spool ADIGT inspired by GE LM6000 and GE LMS100 engine cores respectively are assessed. These two are regarded as representatives of large-scale ADIGT (LS-ADIGT).
- Simulation of advanced cycles: ICR, RC, and intercooled (IC) engines of same cores as the SC engines
- Establishing performances of the ADIGT models at design and off - design conditions.
- Engine emissions estimation of the ADIGT is carried out by the method of applying HEPHAESTUS code, description of which is given in section 2.9.3.

- Performances of the various aero-derivative engine configurations are compared in their respective categories.
- Modelling CHP performances of the small, and large-scale ADIGT is implemented to form simple and advanced cycles ADIGT-CHP. Detail methodology is presented in chapter 5.
- For application in the petrochemical industry, techno-economic and risk assessment of the simple and advanced cycle ADIGT-CHP is done. Detail TERA methodology is presented in chapter 6.
- Techno-economic and risk assessment is implemented by developing a techno-economic model using case studies to assess and predict the viability of the ADIGT-CHP in terms of net present value (NPV), internal rate of return (IRR), and simple payback period (SPBP).
- Risk and sensitivity of NPV with respect to key inputs are analysed of the ADIGT-CHP.
- Comparison of the viability of the various ADIGT-CHP in their respective categories is done.
- The research relies on public domain open source references for data.

Both parts of this research are linked as shown in the diagram of Figure 1-2.

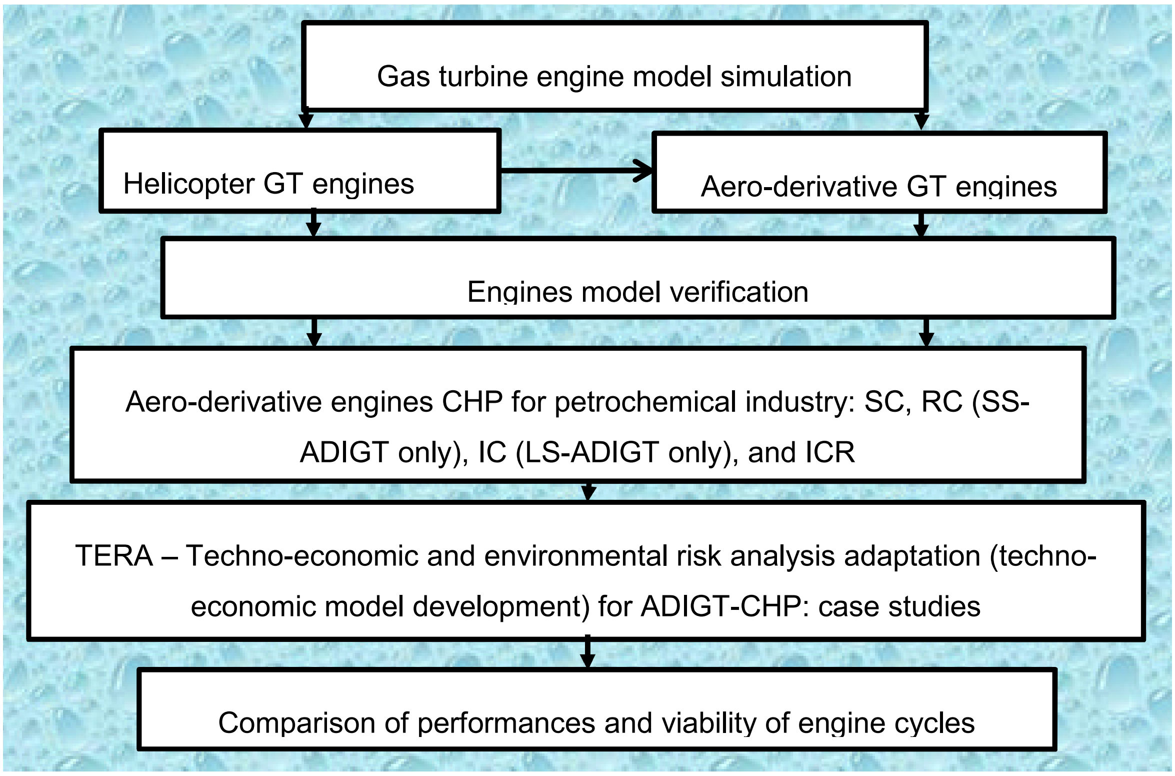

Figure 1-2 Research methodology overview

1.7 Thesis structure

This Thesis comprises of eight (8) chapters as follows:

Chapter one (1) is a general introduction of the research. The background of the research and the justification of study is contained in this chapter. Mention is also made of the research gap and need (presented as research scope) that this research sought to address in the various thematic areas. Besides, the aim, objectives, brief description of work carried out, contribution to knowledge, research methodology overview, approach adopted, and thesis structure are presented.

Chapter two (2) presents the review of relevant literatures, highlighting various research that have been carried out by others in the areas of helicopter engines performance, aero-derivative gas turbines performance, combined-heat-and-power, gas turbine engine emissions, and techno-economic and environmental risk analysis, which are the themes of this research. In relation to these previous researches the scope of this research is also highlighted. It also presents a brief history and the general principles of gas turbine cycle, and its preliminary design concepts. The method of GT performance analysis using TURBOMATCH code is presented. Also, GT engine emissions concept and dry low emission/NOx are defined. Besides, The method of GT emissions prediction using HEPHAESTUS code is presented.

Chapter three (3) presents part A of the research which is about the analysis of simple and advanced cycle helicopter gas turbines performances. The methodology of GT engines performance making reference to TURBOMATCH code is presented. Selection of helicopter engine core, design and off-design points performance simulation of SC, RC, LPC-ZS, and ICR cycle configurations of same core are presented.

Chapter four (4) is the documentation of the analysis of aero-derivative industrial gas turbines (ADIGT) performance applying same methodology stated in chapter 3. This is the beginning of part B of the research. The performance analysis and derivation of SC, RC, and ICR small-scale (SS) ADIGT from the helicopter engines are accounted for. More so, performances of the SC, IC, and ICR, large-scale (LS), ADIGT are analysed. Besides, estimation of engine emissions of the ADIGT by the method of applying HEPHAESTUS code is presented.

Chapter five (5) is composed of the analysis of the ADIGT-CHP performance in the petrochemical industry and the methodology used. It x-rays the performance modelling of CHP with heat recovery steam generator (HRSG) using pinch technology. Applying this technology to analyse the performances of SS-, and LS-ADIGT-CHP guarded by usage in the petrochemical industry is presented.

Chapter six (6) highlights the methodology of TERA used for ADIGT-CHP application, defining the various modules that constitute the framework. More importantly, the algorithm for the techno-economic model developed in this research is laid in this chapter, highlighting the various input and output components of the model. In addition, Risk/probability distribution sampling technique as applicable in @Risk 6.0 software was explained.

Chapter seven (7) documents the TERA implementation case studies for ADIGT-CHP application in the petrochemical industry, where the economic model is developed and deployed. Two case studies are considered one for small-scale ADIGT-CHP, and the other for large-scale ADIGT-CHP. In each case, the model computes the NPV, IRR, and SPBP for all cycle configurations to predict their viability over a conventional case, and values are compared. In addition, risk and sensitivity assessment of predicted mean NPV with respect to uncertainties in some key input values are presented.

Finally, chapter eight (8) outlines the thesis conclusions, aim and objectives achieved, contribution to knowledge, and recommendations for further study based on the research limitations. Besides, the gains of the techno-economic model developed in this research over previous models reviewed are outlined.

1.8 Chapter summary

The following are described in this chapter

- The background of the research and the need that justifies undertaking it are explained.
- The research gaps and needs that would be addressed in this research are described as research scope.
- The technical question to which this research seeks answer is clarified.
- The main purpose of carrying out this research which is the aim is defined.
- The various objectives and tasks to be implemented in order to achieve the aim are highlighted.
- Two contributions that this research would make to knowledge are outlined.
- A general overview of the methodology and approach used in this research is documented.
- The contents of this research are grouped in a structure that make up the Thesis.

2 LITERATURE REVIEW

2.1 Review of past research

The concept of techno-economic and environmental risk assessment generally is not new neither is the application of its philosophy in the field of gas turbine performance analysis invalidated. Several researches have previously been carried out by professionals and researchers. These researches pertain to performance, effective asset management, optimisation, and risk mitigation of gas turbine power plants. It is essential to have insights into the nature techno-economic and environmental risk analysis has appeared and perhaps the various results obtained of its concept application in diverse business scenarios. There are pointers to the fact that this assessment concept has been validated in the areas of aircraft jet engines, marine vehicle propulsion, and liquefied natural gas operations.

Besides, helicopter engine performance analysis in civil aviation is a stale subject of research with enormous stock of interesting results and engine advancements. More so, the application of aero-derivative gas turbines as prime movers in industries has long been embraced as supplements to heavy duty industrial gas turbines, and methods have been developed severally to improve and advance engine performance. Furthermore, combined-heat-and-power generation has come to stay as a formidable and advantageous alternative to producing industrial thermal power and steam separately.

2.1.1 TERA tool

Ogaji et al (2007) explained the emergence and application of a tool called TERA – techno-economic and environmental risk analysis. It was asserted that TERA tool was a brainchild conceived at Cranfield University, which resulted from research work carried out in areas of multi-disciplinary optimization and management of power plant; and, after-come on the environment of both the design and operation of power plants. In their work, TERA framework was applied in aero-engine modeling and management by integrating the tool with a commercial optimizer called iSIGHT - a product of Engineous Software Ltd. The application of TERA tool was demonstrated using a three spool turbo fan (TSTF) engine of conventional configuration and considered its performance at the cruise state of the aircraft. This was done by comparing two case studies: one on a baseline aircraft and the other an optimized aircraft, having the same TSTF arrangement, payload, and range. The thrust, weight and geometry scaling were optimized and it was found that the optimized aircraft had a lesser take-off weight than the baseline aircraft.

Also, efficiency deterioration was simulated with 2% and 4% deterioration on both aircrafts, and it was rightfully observed that there was increase in fuel burn in both cases but the change in fuel burn was more pronounced in the scenario of the optimized aircraft than that of the baseline aircraft. This implies that an aircraft asset manager would appreciate the effect of engine deterioration to make a better decision with an optimized aircraft than with a baseline aircraft. Hence, the significance of TERA application cannot be over emphasized in improving the performance and maintenance management of aero-engines. However, it was suggested from the study that the application of TERA be extended to stationary industrial gas turbine power plants in the near future (Ogaji et al, 2007).

Furthermore, Khan et al (2011) carried out a research on technical risk analysis of gas turbines for natural gas liquefaction in which the risk assessment aspect of TERA was focused upon. Monte Carlo simulations was applied to three 87MW single spool type, industrial machines to compare the risks of introducing new plant equipment against existing and established one. The three cases examined were using: a baseline engine, an engine with increased firing temperature, and an engine with a zero staged compressor. This was done with the intent that the latter two would be modelled as upgrades of the baseline engine between which there will lie the preferred choice judging by their analysis results. The aim was to select gas turbine plant equipment for liquefaction of natural gas. In doing so, machine downtime was identified as an empirical measure of technical risk, and a model that drew correlation between a modified technology readiness level (TRL) and downtime was developed. The analysis was handled with a code that computed the mean time between failure (MTBF), the mean time to repair (MTTR), and the total time to repair (TTTR) of some chosen number of components of the examined power plants.

In their work, two modules of the TERA framework were demonstrated in detail, namely: the lifing, and the risk modules. The engine components life was modelled in the lifing module using the Weibull distribution together with the log normal distribution. In each case three types of failures were considered. These are premature, random, and wear-out failures. Also, the values of scale parameter and shape parameter for each type of failure were varied. Applying the Monte Carlo simulation technique of parametric model, the MTBF, MTTR, and TTTR were estimated of the three engines, and risk results obtained.

It was shown that both the upgrade alternatives give greater power than the baseline engine, but the zero staging option gives a slightly lower power increase than the increased TET option. Also, the increase in efficiency of the zero staged engine is better than the case of the increased firing temperature. Regarding the risk result, it was noted that the study tried to show the philosophy underlying the tool and modelling. More so, it was asserted that the aim was not to give exact answers but to merely typify the gradation in reliability given variations in engine cycle and ensuing performance. More so, the study also aimed at showing the responsiveness and asperity to changes that occur within upgrades of the same engine. However, the risk result showed that the zero staged engines is better than the increased TET upgrade.

Judging by the results, it was suggested that zero staging was preferable to increasing the firing temperature if the baseline engine was to be upgraded, seeing that zero staging rendered lower rise in total downtime (TTTR). They also recommended that to provide an arena for total risk assessment, the demonstrated risk analysis should be integrated with a maintenance cost/scheduling model, and in turn annexed with emissions modeling in order to obtain the overall TERA tool for choice of LNG technology (Khan et al., 2011).

Doulgeris et al (2012) applied TERA for advanced marine propulsion systems where numerical methods were developed to simulate the life-cycle operation of marine gas turbines installed on marine vessels. The framework used comprised of the following: ship performance model which simulated engine performance and exhaust emissions; creep-life prediction method which assessed the life of the gas turbine; and an economic model which was used to predict the life-cycle net present cost of the ship operation (Doulgeris et al, 2012).

2.1.2 Helicopter engines performance

The introduction of gas turbine has caused tremendous revolution in helicopter operational capabilities by improving engine power to weight ratio. Similar improvements in engine performance and other components parts are expected to continue in the foreseeable future. There have been several programmes targeted at helicopter engine performance improvements over the years. In 1968 and 1971 predictions were made of the improved technology of helicopter engines that would be in production by the year 1980. In these predictions forecasts were made based on cycle and component analyses that at the design point a specific fuel consumption (SFC) of about 0.5lb/shphr (0.0912kg/kWhr), an overall pressure ratio (OPR) of about 14, and turbine inlet temperatures (TET) of about 1300 – 1550K would be achieved. This indicated an increase of about 17% in OPR, 7% in TET, and a decrease of about 17% in SFC over the respective values as at that moment (Langshur and Palfreeman, 1971).

Vickers (1995) investigated the potential of the growth of turboshaft engine of a helicopter with time, customer taste, and technological advancement. He considered different methods that could be employed to positively influence the growth (improvement) of the performance of the engine. Such performance growth could be in the area of improving the power output and the specific fuel consumption. It was also noted that user requirement such as larger helicopter size for increased number of passengers which is a growth function could call for modification of existing engine components and performance to satisfy the growth demand. This may affect the size and hence cost of engine.

The aforementioned potential was studied by modifying the preliminary design of the Rolls-Royce/Turbomeca RTM 322 engine model through design and off-design point performance simulations. The methods of modifications that were investigated include increasing the turbine entry temperature, and zero-staging the LP compressor with increasing the non-dimensional flow through the power turbine. From the trends of results, Vickers noted that all the methods investigated depicted improvement in engine performance in the aspects of improving power output, SFC, and cycle efficiency (Vickers, 1995).

2.1.3 Aero-derivative industrial gas turbines

As the name implies, aero-derivative industrial gas turbines (ADIGT) are gas turbines derived from aircraft gas turbines and adapted for industrial power generation. It has been reported that the introduction of modern, high thrust aero-engines for aircraft propulsion has resulted in the development of a commensurate range of new high power, high efficiency ADIGT. This is illustrated by the Rolls-Royce TRENT. The development of these large, efficient ADIGT offers particular chances for use in power generation and combined-heat-and-power plant. ADIGT give various advantages over their industrial design counterparts, in technology, project implementation and maintenance. Comparing performance, modern ADIGT present a very efficient form of simple cycle energy conversion and this is exemplified in the TRENT GT. The high efficiency of the TRENT engine makes it a distinct choice for simple cycle application.

With a state-of-the-art technology development from a modern aero-engine, fiscal studies have indicated that the high efficiency aero-derivative version exceedingly counterpoises for higher first cost that could be expected. Modern ADIGT are also a feasible option for CCGT and CHP applications where power in the 60 - 120 MW class is anticipated. The TRENT GT, having a combined-cycle efficiency of about 51.5%, is one of the most competitive options available in its class. Modern ADIGT plants are an amply-embraced alternative for energy generation and this progression is expected to advance with the TRENT and future developments (Smith, 1996).

The GE LM6000 aero-derivative gas turbine series has undergone some new innovations in technology especially those in the 35 – 65 MW_e range. The GE LM6000 has the latest innovations in the LM6000PG & PH versions. These are denoted as the "PG" for the standard annular combustor (SAC) and "PH" for the dry low emissions (DLE) model. The improved technologies for these new products include new higher temperature alloys and improved cooling pattern to withstand high combustor outlet temperature, LP compressor operating at higher speed and increased mass flow, and higher pressure ratio. The GE LM6000 PG offers a 25% simple cycle power increase compared to the GE LM 2500, its predecessor, owing to advanced technology (Mehmetli et al, 2010). The advancement to the GE LM6000 gas turbine produces an 18% increase in the exhaust energy and 25% increase in power, and about 52% combined-cycle efficiency when incorporated into a 2-on-1 reference combined-cycle plant (Mehmetli et al, 2010).

2.1.4 Combined-heat-and-power

Polyzakis (2004) carried out research on combined-heat-and-power in which he took into account changes in ambient conditions and power settings of a tri-generation power plant, utilising an evaluation tool for combined heat, cooling and power generation plant. The work was based on an overall techno-economic analysis of the tri-generation system that comprised energy demand analysis and evaluation of actual tri-generation case studies, modelling of the prime mover (Gas Turbine, GT) and absorption cooling system (LiBr/Water), and, economic analysis and evaluation of the entire tri-generation plant. He conducted technical assessment by way of modelling and simulation of the Design Point (DP) and Off Design (OD) analysis of the gas turbine.

The performance analysis simulated different thermodynamic cycles (Simple, or with Heat Exchanger), and different configurations (one or two shafts). Also, the computer programming code was able to simulate the effects of the use of different types of fuel, ambient conditions, part load conditions, degradation, or the extraction of power for district heating or for absorption cooling. Part of his technical assessment was the simulation of the absorption cooling system alone and in conjunction with the prime mover. The simulation was based upon the premise that the original prime mover was replaceable (Polyzakis, 2004).

Polyzakis then introduced an evaluation methodology of tri-generation plants, considering both technical facts and economic data based on certain cases from Greek reality, thereby, helping potential users to decide whether it is profitable to use such technology or not. The economic scene involved basic economic facts such as initial cost, handling and operational cost (fuel prices, maintenance etc), using methodology based on Net Present Value (NPV). Case studies were conducted to evaluate CHP trigeneration application in the following scenarios: The new International Macedonia Airport of Thessaloniki, Greece; Lemnos Island; Rhodes Island; Hotel in Rethimno-Crete; and, Hotel in northern Greece. Besides, a sensitivity analysis was also carried out concerning: national electricity price, purchase electricity price, oil price, natural gas price, and CO2 penalty price.

His results suggested that the 2-shaft simple cycle tri-generation technology mode was more economically favourable than the conventional technology for the cases of international airport (12MW total power demand) and the isolated island (120MW), while the 1-shaft simple cycle mode was more economically favourable for the case of hotel (1MW). Finally, he inferred that a valuable integrated tool was provided which could simulate the future operation (technical and economic) of a trigeneration plant, and capable of helping potential investors decide if it is profitable to proceed with their investments in such technology. He, nevertheless, recommended that in future studies, consideration be accorded emission penalty for NOx in addition to CO2 (Polyzakis, 2006).

The possibilities to develop combined-cycle units (CCU) based on ADIGT and existing steam turbines have been investigated. The specific compatibility problems of these components and the thermodynamic performances of the analysed CCU were also identified. It was found that the thermal efficiency of CCU is higher than that of individual gas turbine GT or steam turbine ST unit (about 16 – 18% more than GT and 6 – 8% more than ST). Thus thermal efficiency of the studied CCU was higher than that of the most efficient power units operating in Romania at that moment (Talif, 2010).

2.1.5 This research

This research investigates technical performance of advanced cycle helicopter engines by the use of additional components. Such advanced cycles include, recuperated, intercooled-recuperated, and Low pressure compressor (LPC) zero-staged cycles. Also, conversion of helicopter engines to small-scale (SS) ADIGT is carried out, and their application in CHP in the petrochemical industry investigated.

Besides, in this research, application of simple and advanced cycle large-scale (LS) ADIGT in CHP to generate power and process steam in the petrochemical industry is considered. More importantly, adaptation of TERA as a preliminary design and decision making tool for assessment of the viability of the SS, and LS, ADIGT in CHP cycle options in the petrochemical industry is implemented. By so doing, a techno-economic model is formulated and developed to compute the NPV, IRR, and SPBP of the ADIGT-CHP cycles putting into account, capital/installation cost, total emissions cost, fuel cost, O&M cost, etc. The emissions accounted for here include NO_x, CO, H_2O_{vapour}, and CO_2 rather than only CO_2 as recommended in Polyzaki's work. Also, previous work only estimated NPV, whereas this work includes estimation of IRR, and SPBP.

Furthermore, risk and sensitivity analysis of mean NPV of the ADIGT-CHP cycles with respect to uncertainty in values of gas fuel, grid electricity tariff, electricity export price, and total emissions tax, are investigated employing normal, triangular, and uniform probability distribution of inputs.

2.2 History of gas turbine

According to Singh (2011), the underlying principles of gas turbine were described in British Patent Number 1833 titled 'A Method for Rising Inflammable Air for the Purpose of Producing Motion and Facilitating Metallurgical Operations'. This patent was retrieved by John Barber in 1791, about the time of the French Revolution. After about 150 years, the principles presented by Barber were transformed into products by Frank Whittle and others. Many attempts had been made to establish a gas turbine that would produce positive power before Frank Whittle's work. Prominent among these trials were the attempt of the Norwegian, Aegidius Elling (1903), whose machine had a rotor design similar to that of Sir Frank Whittle; the German, Stolze (1900 – 1904) had a gas turbine which incorporated a multi-stage axial compressor and a multi-stage axial turbine, but the machine apparently never rotated; the German, Holzwarth (1906-1908) had a two-stage Curtis turbine built by the Swiss, Koerting (1903 – 1913); the French, Armengaud and Lemale (1903 – 1905) had an internal combustion gas turbine which had a radial compressor and a single stage impulse turbine wheel (this project apparently did result in excess power, but also included the injection of steam and the project was abandoned in 1909 when Armengaud died); the American, Stanford Moss (1903-1904) had a design very similar to those of the French, but the project was also abandoned. This period witness the registration of a number of patents. It was the Norwegian, Elling, who is credited with having run in 1903 the world's first gas turbine to give excess power (Singh, 2011).

The inception of World War II witnessed the emergence of Gas turbine with focus on electricity generation. Then steam turbines and diesel engines were the widely used prime movers for power generation. Just before the end of World War II gas turbine got its first pronounced use in developing the military jet engine. Then it produced a significantly greater speed compared to the aircraft driven by propeller. About 20 years later gas turbine became the major means of civil aircraft propulsion. Today the gas turbine has gained substantial impact even in the non-aircraft market (Saravanamutoo et al, 2009).

2.3 Brayton cycle

About 1870 George Brayton first introduced the concept of Brayton cycle for application in the reciprocating oil-burning engine that he developed (Lane, 2001). Brayton cycle is the ideal thermodynamic cycle for gas turbine engines. Gas turbine operating on the open Brayton cycle is shown in Figure 2-1. The cycle is made up of an air in-take; a compressor; a combustor with fuel in-flow; a turbine; and an exhaust. The compressor sucks in ambient air though the in-take and compresses it to a higher condition of temperature and pressure. The compressed air flows into the combustor to burn fuel at constant pressure. The gaseous products of combustion expand through the turbine to the ambient condition at the exhaust. By so doing, power is produced in the turbine. Part of the power is used to drive the compressor and the remainder used to drive external loads. Four reversible processes that are internally executed constitute the ideal Brayton cycle. These include: process 1-2 - Isentropic compression which occurs in the compressor; 2-3 - constant pressure heat addition which takes place in the combustor; 3-4 - isentropic expansion occurring in a turbine; and 4-1 - constant pressure heat rejection (in the exhaust) (Gramoll and Huang, 2012; Boyce, 2006). The Brayton cycle could as well be referred to as the simple gas turbine cycle with the annular station numbered configuration as shown in Figure 2-2 below.

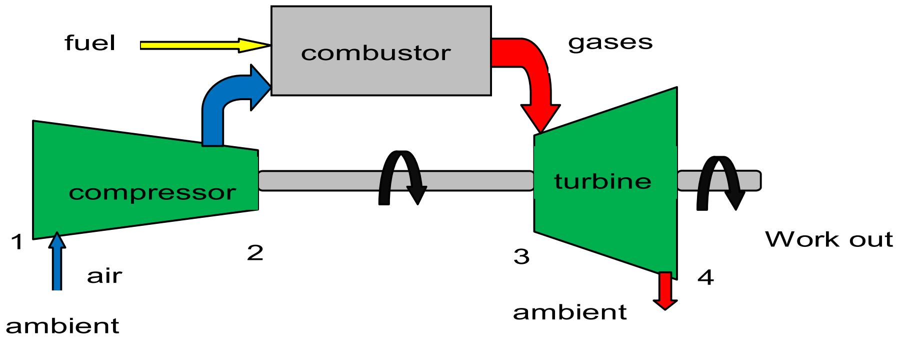

Figure 2-1 An open gas turbine cycle (source: Gramoll and Huang, 2012)

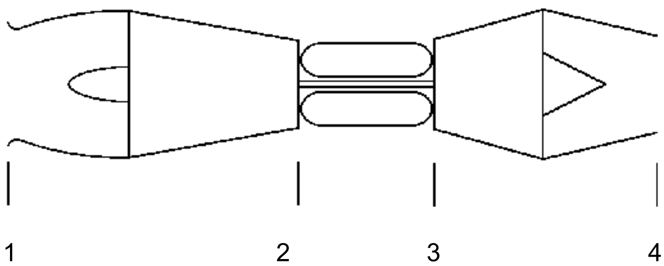

Figure 2-2 Simple gas turbine cycle – Station number designation (Pilidis and Palmer, 2010)

The T-S diagram of simple cycle is shown in Figure 2-3. Heat flow into the cycle in the combustion chamber (process 2-3) per unit air mass flow is given by Equation 2-1.

$$\boldsymbol{q_{in} = h_3 - h_2 = c_p(T_3 - T_2)}$$ Equation 2-1

Where h is specific enthalpy at various stations, c_p is specific heat of air at constant pressure, and T is total temperature at various stations.

Heat rejected per unit mass flow at constant pressure (process 4-1) is given by Equation 2-2.

$$\boldsymbol{q_{out} = h_4 - h_1 = c_p(T_4 - T_1)}$$ Equation 2-2

Compressor work (process 1-2) per unit air mass flow is given by Equation 2-3.

$$\boldsymbol{CW = h_2 - h_1 = c_p(T_2 - T_1)}$$ Equation 2-3

Expansion work (process 3-4) per unit air mass flow is given by Equation 2-4.

$$\boldsymbol{EW = h_3 - h_4 = c_p(T_3 - T_4)}$$ Equation 2-4

Since compression and expansion are isentropic, it follows that Equation 2-5 is true of the relationship between temperature and pressure of air.

$$\boldsymbol{\frac{T_1}{T_2} = \left[\frac{P_1}{P_2}\right]^{\frac{(\gamma-1)}{\gamma}} = \left[\frac{P_4}{P_3}\right]^{\frac{(\gamma-1)}{\gamma}} = \frac{T_4}{T_3} = \frac{1}{\pi^{\frac{(\gamma-1)}{\gamma}}}}$$ Equation 2-5

Where, ϒ and π are isentropic index of expansion and pressure ratio respectively. ϒ could also be referred to as the ratio of specific heats. Then the thermal efficiency is given by Equation 2-6.

$$\eta_{th} = \frac{useful\ work}{heat\ input} = \frac{c_p(T_3 - T_4) - c_p(T_2 - T_1)}{c_p(T_3 - T_2)}$$ Equation 2-6

(saravanamuttoo et al, 2009; Pilidis and Palmer, 2010; Gramoll and Huang, 2012).

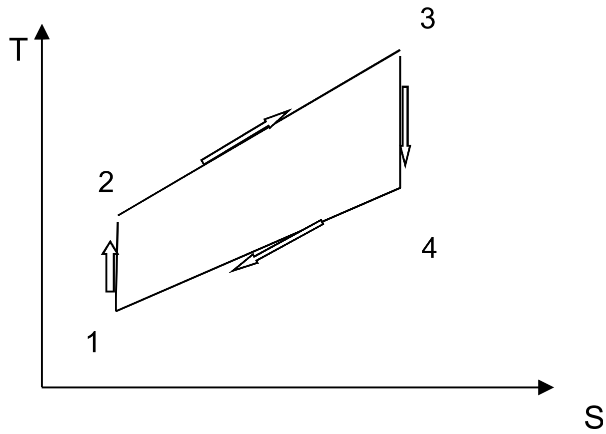

Figure 2-3 T-S diagram of the ideal simple cycle (Gramoll and Huang, 2012)

The cycle thermal efficiency of gas turbine is practically visible when described in terms of fuel flow. The term may be denoted as specific fuel consumption (S.F.C), a measure of engine efficiency, defined as fuel required per unit of power output. It is given by Equation 2-7

$$SFC = \frac{fuel\ flow\ rate}{useful\ power} = \frac{\left(\frac{heat\ input\ rate}{fuel\ calofic\ value}\right)}{useful\ power} \qquad \text{Equation 2-7}$$

But

$$\eta_{th} = \frac{useful\ shaft\ power}{heat\ input\ rate}$$

Therefore, another form of expressing SFC is given by Equation 2-8

$$SFC = \frac{1}{\eta_{th} \times fuel\ calorific\ value}\,[lb\ H^{-1}hr^{-1}] \qquad \text{Equation 2-8}$$

(Pilidis and Palmer, 2010).

This shows that SFC is inversely proportional to thermal efficiency of the engine. Hence, any modification to gas turbine engine that reduces the specific fuel consumption or the fuel flow, surely increases the thermal efficiency of the engine

2.4 Modifications to the simple cycle

In order to increase the thermal efficiency of the simple-cycle, unconventional components are added to the cycle. These components include such like intercooler, regenerator (recuperator), and reheater. However, the initial and operation costs of the cycle may increase due to these additional components. The improvements in cycle performance brought about by these components can only be justified if the decrease in fuel costs offsets the increase in other costs. There is the general urge to reduce fuel consumption in gas turbine operation (Lane, 2001). This is achieved by the introduction of these modifications to the simple cycle. This has led to the emergence of advanced gas turbine cycles namely: recuperated (regenerative), intercooled, intercooled-recuperated, and reheat cycles (pilidis and palmer, 2010; Saravanamuttoo et al, 2009).

2.5 Actual gas turbine cycles

In the cycle described in section 2.3 it has been assumed that the compression and expansion processes occur adiabatically and reversibly (that is they are isentropic), a no losses situation, where there is no increase in entropy. In reality, this is normally not the case, because losses such as friction drag, do happen and this eventually would cause higher compression work. Thus, there is irreversibility in real (actual or practical) cycles, considering isentropic efficiencies of compressors and turbines (pilidis and palmer, 2010; Saravanamuttoo et al, 2009).

2.6 Design point (DP) performance of gas turbines

The Design Point of a gas turbine could be defined as the very condition in the operating range of a gas turbine when the engine is running at the very mass flow, speed, and pressure ratio for which the components were designed (Pachidis, 2008). In establishing the design point of the engine, a mass flow, pressure ratio and TET that results in an overall highest thermal efficiency are normally determined from preliminary cycle calculations. After this is done, other appropriate design parameters of the gas turbine system may be allotted. Then, detail design of different engine components can be done in order to provide the specified requirements of the complete system when operating at the DP. There are many requirements from a gas turbine engine depending on the engine application(Pilidis and Palmer, 2010; Li et al, 2006).

2.7 Off design (OD) performance of gas turbines

Besides the DP performance of the gas turbine, it is mandatory to ascertain its general performance over the entire operating range of power output and speed. This is known as Off-Design (OD) performance (Pachidis, 2008). Component characteristics as indicated by component maps of compressor, turbine, and combustor, are very useful in ascertaining off-design behaviour of the gas turbine system. These are plots of component parameters such as pressure ratios versus corrected mass flow rates at various corrected speeds, and component efficiencies versus pressure at different corrected speeds. At steady state operation of the engine, corresponding operating points on the component maps are matched and can be plotted on the compressor characteristic diagram to form an equilibrium running line. This running line should lie near the region of compressor maximum efficiency.

Various performance plots of power output, specific fuel consumption (SFC), thrust, specific thrust or power, etc could be made once the operating conditions of an engine have been determined. It is important to note that off-design performance is very much affected by factors such as ambient conditions of temperature and pressure, altitudes, flight speed (for aero engines), etc. For instance, industrial gas turbines have to operate between ambient temperature of about -60^{o}C in the arctic region and 50^{o}C in the tropics and at altitudes from sea level to about 3000m. Thus, the way gas turbine engines perform with varying operating conditions is obviously an essential safety and economic matter. More so, variations in engine power demand also determine off-design behaviour of an engine (Pilidis and Palmer, 2010). The design point and off-design performance analysis is normally achieved by the use of computer model simulations of engines (Al-Hamdan and Ebaid, 2006). Some effects of changing conditions of gas turbines on performance are illustrated in Figure 2-4, Figure 2-5, and Figure 2-6 below.

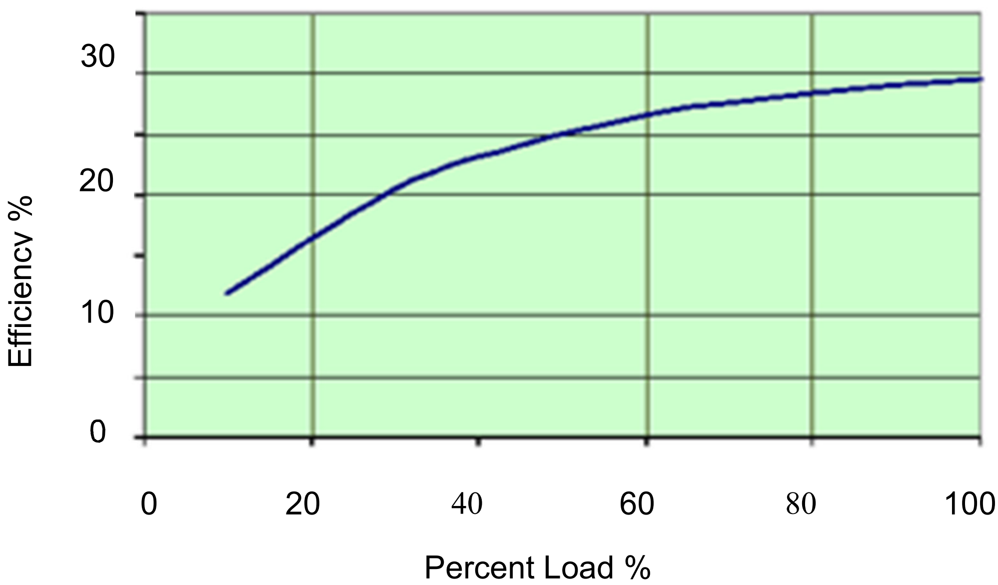

Figure 2-4 Part load power performance (source: Energy and Environmental Analysis, 2008)

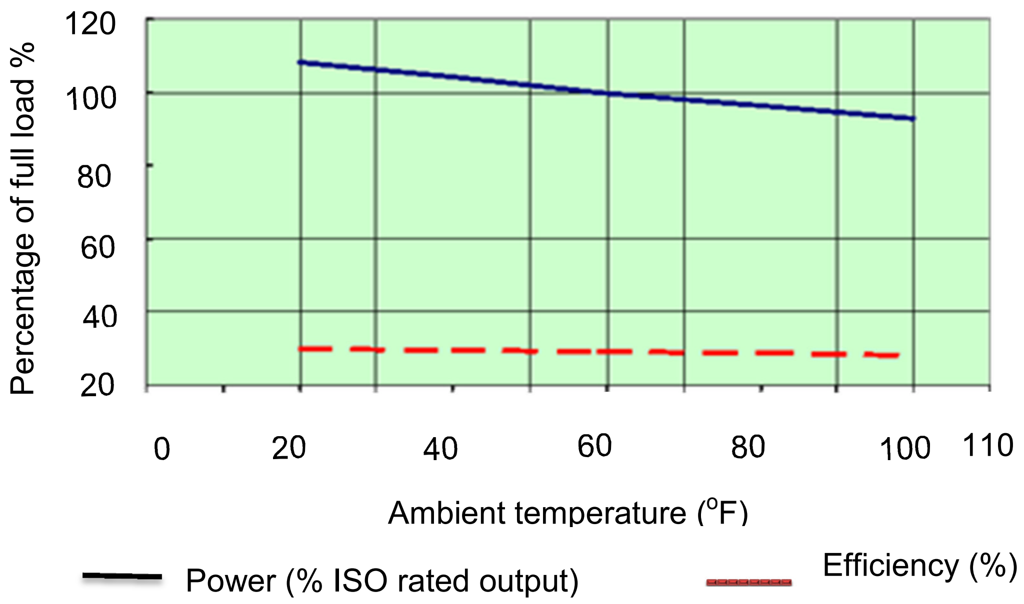

Figure 2-5 Ambient temperature effect on performance (source: Energy and Environmental Analysis, 2008)

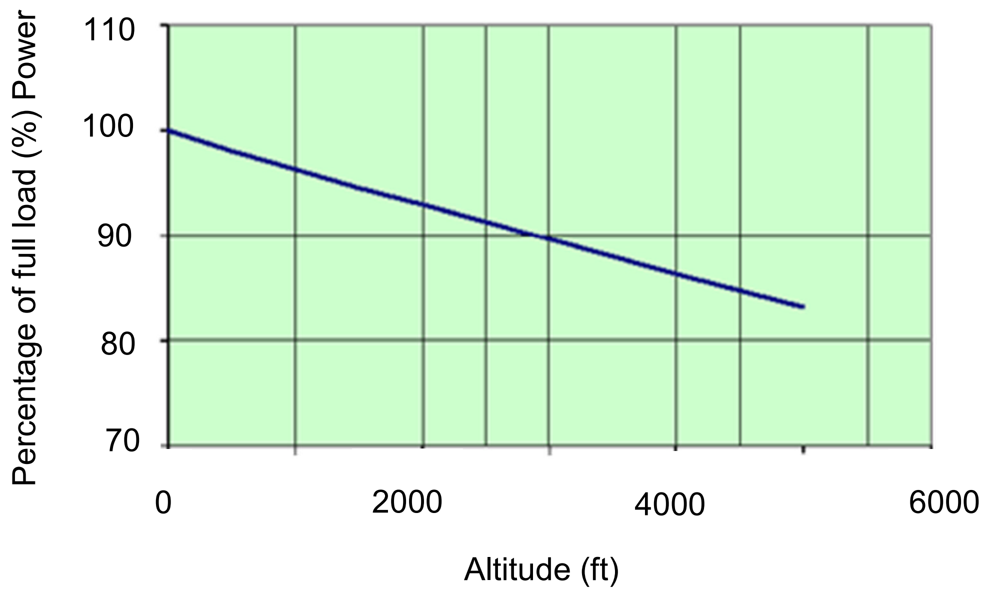

Figure 2-6 Altitude effects on performance (source: Energy and Environmental Analysis, 2008)

2.8 TURBOMATCH – engine performance prediction code

Engine components operating point matching to establish DP and OD performance is normally a tedious and time consuming task since it is an iterative process. For this reason, computer based simulation is normally employed to accomplish the task. TURBOMATCH is a gas turbine engine performance code developed and established at Cranfield University. It is employed to simulate the DP and OD performances of a broad range of aero and industrial gas turbines. Simple single shaft engines, complex multi-spool engines, as well as novel cycle engine configurations can be modelled adequately using the scheme. It is a programme that has the capability to simulate both steady state performance and transient performance characteristics.

In the scheme, different engine components (intake, compressor, combustor, turbine, nozzle, etc) are represented by bricks (building blocks of the programme). These bricks are pre-programmed routines deployed to simulate, on a modular basis, the performance of the various engine components they represent. The cycle thermal efficiency, specific fuel consumption, power, or thrust of the engine, etc are essential performance output parameters that are obtained as desired results of the simulation. Besides these overall cycle results, individual component performance characteristics, and the working-fluid properties at various stations within the engine are also outputted. TURBOMATCH scheme is inter-face friendly and presented in a way that computer programming non-experts can conveniently use. Apart from the bricks that represent specific engine components as outlined above, the programme also consist of other bricks that perform various arithmetical operations, take care of final performance calculation, and produce additional output.

More importantly, the gas states at the inlet and outlet to every component brick are defined by a number of quantities called station vectors. These gas states describe the thermodynamic processes taking place within the component. The numbers of quantities that constitute each station vector include the following: total and static pressures and temperatures, velocity, mass flow rate, area, etc (Palmer, 1999; Pachidis, 2008).

2.9 Gas turbine engine emissions

Burning fuel in gas turbine combustors generates some exhaust products as emissions. The exhaust from both aero-engines and industrial gas turbines is made of carbon dioxide (CO_2), carbon monoxide (CO), water vapour (H_2O), unburned hydrocarbons (UHC), oxides of nitrogen (NO_x), particulate matter (carbon), and excess atmospheric oxygen and nitrogen. Of these products, H_2O and CO_2 only contribute to global warming but are not classified as pollutants. These two could be reduced by reducing fuel consumption (Lefebvre and Ballal, 2010). Table 2-1 Presents list of major pollutants.

Table 2-1 Principal pollutants Emitted by Gas Turbines (Lefebvre and Ballal, 2010)

Pollutant	Effect
Carbon monoxide(CO)	Toxic
Unburned hydrocarbons (UHC)	Toxic
Particulate matter (C)	Visible
Oxides of nitrogen (NO_x)	Toxic, precursor of chemical smog, depletion of ozone in stratosphere
Oxides of sulphur (SO_x)	Toxic, corrosive

The amount of pollutants produced in gas turbine combustion is directly proportional to the temperature, time and concentration histories of the combustion process. This varies with changing operating conditions of any given combustor. At low power settings the concentrations of UHC and CO are highest and decrease as power increases. On the contrary, the concentrations of smoke and NO_x are minimum at low power settings and increase to maximum with increasing power (Lefebvre and Ballal, 2010).

2.9.1 Emission index (EI)

Emission index of a gaseous product of combustion is defined as the ratio of the amount of product in grams to the amount of fuel consumed in kilograms. For instance, emission index of NO_x denoted by $EINO_x$ is given by Equation 2-9.

$$EINO_X = \frac{g\ of\ NO_X}{kg\ of\ fuel} \qquad \text{Equation 2-9}$$

Similarly EICO, $EICO_2$, and EIH_2O are calculated. These quantities are computed and translated into annual total emissions based on the amount of fuel consumed (Khan et al, 2009).

Total emissions is given by Equation 2-10.

$$Emission\left(\frac{g}{kW}\right) = EI\left(\frac{g}{kg\ fuel}\right) \times SFC\left(\frac{kg\ fuel}{kWs}\right) \times Time(s) \qquad \text{Equation 2-10}$$

(Lefebvre and Ballal, 2010).

2.9.2 Dry low emission (DLE), or NOx (DLN)

A major factor that influences the emission of NO_x and CO is the combustor primary-zone temperature. An attempt to increase the primary-zone temperature to a value above 1900K favours the formation of excessive amount of NO_x and low amount of CO emissions. The reverse effect is the case when the primary-zone temperature is reduced to value below 1680K which is low NO_x and high CO. Thus, as illustrated in Figure 2-7 , a temperature "window" for low emissions is created in which both NO_x and CO emissions are kept to a minimum value. Over time this temperature "window" shrinks narrower as stricter emissions regulations evolve (Lefebvre and Ballal, 2010).

The combustion zone ought to be maintained within the temperature "window" of low emissions for the entire power setting range of the engine. To do this some measures have being adopted for emissions reduction. Dry low emission (DLE) or dry low NOx (DLN) technologies have emerged as techniques to maintain combustion within the temperature "window" of low emission without the use of water or steam injections. Air dilution of the zone is used instead of water or steam, hence, the "dry" low concept.

DLE or DLN concepts are applied in various combustion technologies such as: variable geometry combustion, stage combustion, and lean pre-mixed/pre-vapourised (LPP) combustion.

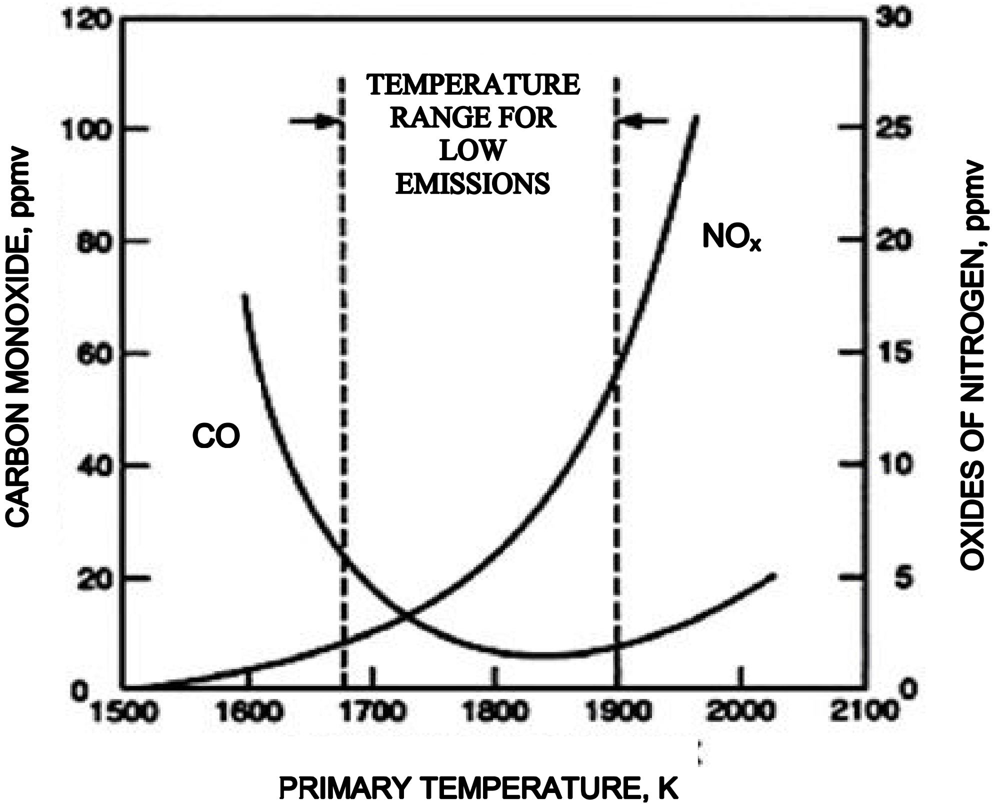

Figure 2-7 Influence of primary-zone temperature on NOx and CO emissions (source: Lefebvre and Ballal, 2010)

2.9.3 HEPHAESTUS-engine emissions prediction code

A code called HEPHAESTUS – adapted for industrial gas turbines has been developed at Cranfield University, UK and validated to perform the engine emissions and environment module of TERA. The scheme simulates a single annular combustor, and introduces a technology factor so that it can calibrate the amounts of engine emissions to standards that apply to different technology combustors. The model is capable of simulating combustion of variety of fuels, namely: Jet-A, natural gas, biofuels, and blended jatropha-jet A. Applying DLE concept, the key input parameters to the code are: ambient altitude, ambient temperature, ambient relative humidity, air total temperature at combustor inlet, air total pressure at combustor inlet, total air mass flow rate, flame front air mass flow rate fraction, primary air mass flow rate fraction, intermediate air mass rate flow fraction, dilution air mass flow rate fraction, fuel mass flow rate, and fuel total temperature (Celis, 2010; Kyprianidis, 2008).

The scheme utilized physics based approach of the stirred-reactors strategy for emissions estimation. This is because this approach combines some desired features of both empirical correlations approach and CFD calculations. Three concepts of stirred-reactors strategies are employed by the model, namely: perfectly-stirred reactors, series of perfectly-stirred reactors, and partially-stirred reactors (Samaras et al, 2011).

Emission indices of the gaseous products at different power settings and ambient temperatures, and the total quantity of each emission are calculated. These combustion products include oxides of nitrogen (NO_x), carbon monoxide (CO), unburnt hydrocarbon (UBH), carbon dioxide (CO_2), and water vapour (H_2O_{vapour}), which constitute bulk of nuisance to the environment (Celis, 2010; Kyprianidis, 2008).

2.10 Techno-economic and environmental risk analysis

Techno-economic and environmental risk analysis (TERA) framework is a multi-disciplinary tool developed to model gas turbine and aircraft performance, measure engine emissions, noise, weight, and also to estimate environmental impact and the economics of operation. TERA framework is a brainchild conceived at Cranfield University, which resulted from research work carried out in areas of multi-disciplinary optimisation, asset management, of power plants, and effect of power plant design and operation on atmospheric pollution. TERA tool is utilised to assess and optimise potential, as well as, existing engine designs for the purpose of minimising development and ownership cost. Its philosophy as illustrated in LNG plant operation and aircraft optimisation is shown in Figure 2-8 and Figure 2-9 respectively.

TERA philosophy is conceived to consist basically of the following modules:

- Aircraft performance module: This module which is coded as HERMES, was developed to calculate the following data that depict the performance of the aircraft: the lift coefficient, drag coefficient, distance to take-off, fuel usage, time elapsed, distance covered, and the range for a given fuel load, maximum take-off weight, and payload.
- Engine performance module: TURBOMATCH modeling code is used as the engine performance module. It is an in-house gas turbine performance assessment tool of Cranfield University. It is a computer programme which evolves data from the machine required for other TERA modules, such data as specific fuel consumption (SFC), cycle efficiency, power output, mass flow etc.
- Economics module: Three sub-modules namely; risk, economic, and lifing, modules comprise the economics module. This module measures the life of the high pressure turbine disk and blade (using failure analysis of creep and fatigue). It also measures the maintenance cost of the engine and the net present cost of operation. More so, associated risk is estimated using the Monte Carlo method.
- Environment module: A parametric model – the general circulation model (GCM) simulation is used to estimate the global warming potential (GWP) index to assess the environmental impact for a given aircraft mission.
- Noise module: A noise estimation program called SOPRANO, an acoustic prediction code is applied to estimate the aircraft noise. This noise reduction technology assessment code was developed by the company ANOTEC Consulting. They estimated the Effective Perceived Noise Level – EPNL of fan, jet and airframe, being the three major sources of noise. This was extended to atmospheric absorption and ground effects to simulate the noise propagation from the aircraft.
- Emission module: This module computes the concentrations of the exhaust pollutants namely, oxides of Nitrogen (NOx), carbon monoxide (CO), and un-burnt hydrocarbons (UHC). The data required by the economic and environment modules are fed from the emission module to allow for the prediction of emission taxes and GWP accordingly.
- Weight and geometry module: Engine and component materials, geometry, and weights, which are required by other TERA modules, were obtained from this module.
- Manufacturing plant cost module: This module uses a bottom-up approach to estimate the cost of components and that of the engine, thereby giving a direct production cost which show practical cost grading and trending. Inputs to this module include manufacturing technology

levels, production cost, materials prices, available machine settings and production numbers.

- Optimiser: This is the routine that optimises the aircraft overall performance for a given engine performance, weight, and geometry. This is aimed at meeting a defined range and achieving a functional goal of reduced operation cost, reduced concentration of exhaust pollutant, and increased cycle efficiency and output power (Ogaji et al, 2007).

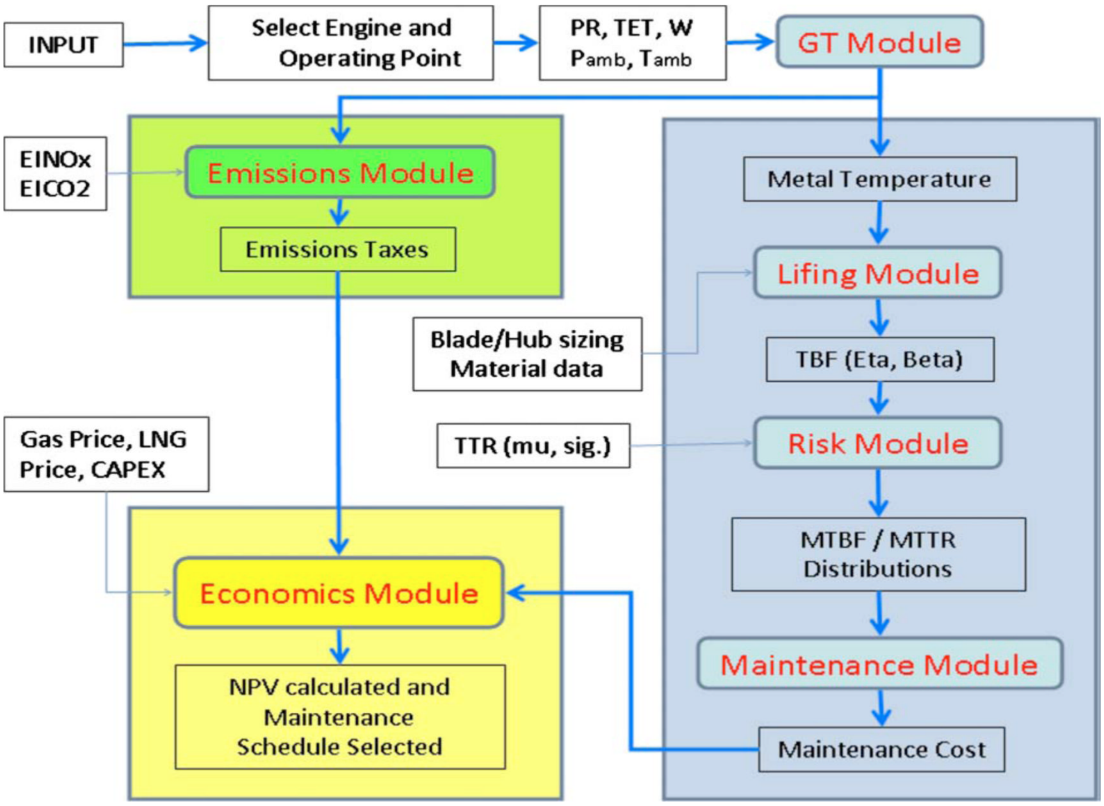

Figure 2-8 TERA framework for LNG application (source: Khan et al, 2011)

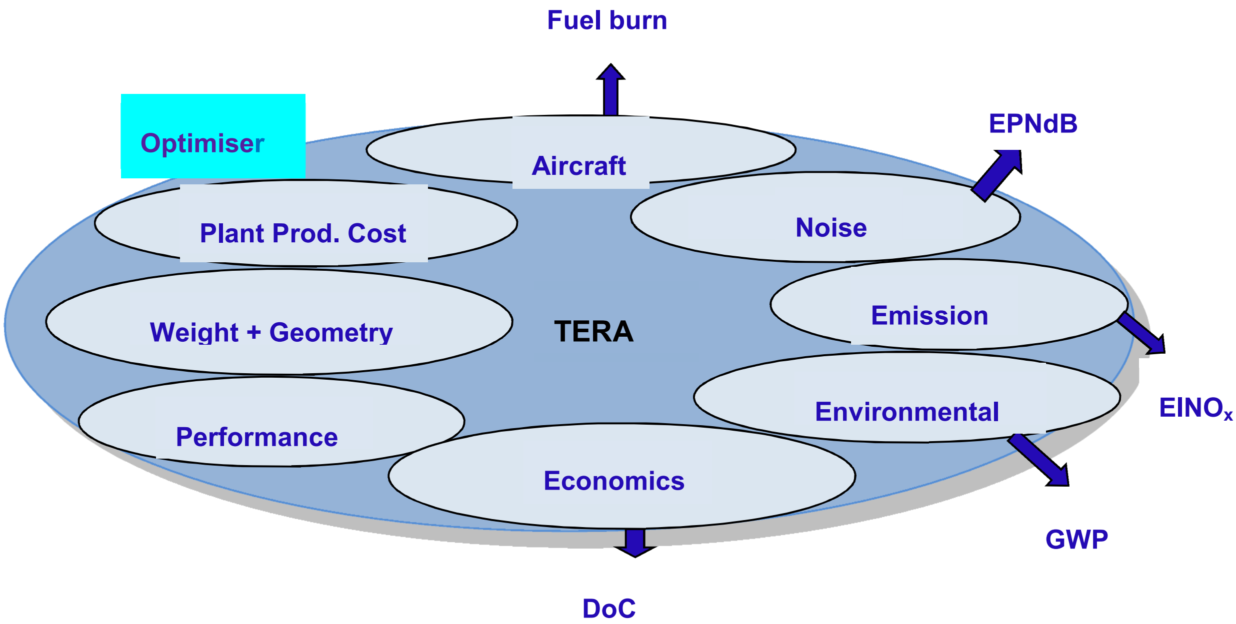

Figure 2-9 TERA philosophy and framework for aircraft optimisation (source: Ogaji et al, 2007)

2.11 Chapter summary

In this chapter the following are explained:

- A review of some past researches carried out in the thematic areas of this research is done.
- Brayton cycle is defined as gas turbine thermodynamic cycle and its theories and principles are highlighted.
- The method of analysis of gas turbine performance using TURBOMATCH code which is adopted in this research is explained.
- The method of analysis of gas turbine emissions using HEPHAESTUS code which is adopted in this research is explained.
- The philosophy of TERA framework which is adapted to ADIGT-CHP in this research is described.

3 PART A: HELICOPTER ENGINES PERFORMANCE METHODOLOGY AND ANALYSIS

3.1 Overview

The performances of engine cycle options of a chosen civil helicopter turbo-shaft gas turbine are investigated. The cycle options are simple (SC) (base engine), and advanced cycles. The advanced cycles consist of recuperated (RC), intercooled/recuperated (ICR), and low pressure compressor zero-staged (LPC-ZS) cycles. The significance of ascertaining the performances of these helicopter engine cycle options is partly because they are to be subsequently considered for conversion to small-scale aero-derivative industrial gas turbines that would be employed for combined-heat-and-power application in the petrochemical industry. A second significance of their performance assessment is to serve as a step towards making good choice of helicopter engine cycles for an envisaged application.

The chapter begins with a look at the nature, characteristics, and functions of a helicopter. Also, it highlights the methods used to analyse the engine cycles which are the thermodynamic principles of turbo-shaft gas turbine. These principles originate from the most fundamental Brayton cycle theory and cumulates to more complex configuration like the two-spool engine. The chapter ends with the design and off-design points performance simulations and comparisons of the helicopter engine cycles. The method of applying gas turbine performance analysis code – TURBOMATCH is adopted to simulate the performances of the helicopter engines. The TURBOMATCH code has been described in section 2.8.

3.2 The helicopter and its function

The helicopter is a rotary-wing aircraft as opposed to the fixed-wing aeroplane. The production of different types of rotary-wing aircraft has been on the increase since World War II. An helicopter manufacturer - Sikorsky introduced the single-rotor helicopter (with tail rotor) during the war years. Since then several versions of helicopters having tandem rotors, side-by-side rotors, coaxial rotors and tip-driven rotors have been established. Another group, tending towards fixed wings now exist which includes compound systems, tilt rotors and tilt wings. The tilt rotor, as the name suggests, is the type in which the rotors face upwards for vertical take-off and hover, and forwards for horizontal flight. The tilt rotor type seems to offer considerable promise and may in the future become the type which would liberate the helicopter from its constraining speed limitation. The helicopter can never fly fast compared to the fixed-wing aircraft, and this limitation is due to the possibility of occurrence of blade stalling. Up till now the single-rotor helicopter remains by far the most numerous the world over (Seddon, 1990).

The helicopter is known to be a distinctive automobile because of its aptness to hover, fly vertically, fly at low altitudes, and manoeuvre. These features make the helicopter very useful in difficult terrain. Its immediate availability makes it the most effective solution for flight to urban areas. Helicopters are used for civilian air transport such as inter-airports and heliports services, air taxi, and business travel. Also, it is used for search and rescue operations, fire-fighting, motorway patrol, aerial photography, power line inspection, pipeline inspection, air ambulance, disaster relief, and traffic monitoring. More so, its use extends to agricultural applications, press and TV coverage, lifting (skycranes), policing, and executive services (Sonneborn, 2003). Helicopters are also used for military and naval purposes like surveillance, transfer of armours or personnel, attacking, support of ground troops, etc (Brown, 1981).

More specifically, the helicopter operates by providing lift, propulsion, and control with the aid of its rotating wings. The rotor blades rotate about a vertical axis, circumscribing a disc in a horizontal or approximately horizontal plane. The motion of the surface of a wing relative to air creates aerodynamic forces. These forces can be generated even when the helicopter is stationary, as opposed to fixed wing aircrafts which need to keep moving in order to maintain flight. This feature makes the helicopter unique in that it is capable of producing vertical flight (vertical take-off, and landing). The thrust force supplied by the rotor must be sufficient enough to support the helicopter weight (Johnson, 1994).

3.3 Helicopter engine: the turbo-shaft engine

Gas turbine engines which provide power for rotary wing aircrafts, or helicopters, are referred to as turbo-shafts. Some major criteria to be considered for helicopter engines are; engine weight, rated SFC, flight speed, and part power SFC. For turbo-shaft engines the frontal area of the engine is not particularly significant because low flight speeds are expected of the helicopter. Part power SFC is important because maximum power may be sized either for hot day operation or for multi-engines in case of one engine failure. Turbo-shaft engines may be single-spool or multi-spool. The single-spool configurations are employed basically to minimise weight. Free power turbine configuration with a single spool or in some cases two spool gas generator characterise turbo-shaft engines. Pressure ratio is usually in the range 7:1 to 10:1 (with TET of about 1250K to 1450K), and up to about 17:1 (with TET of about 1500K), in which cases, blade cooling is required. For specific power, this pressure ratio of 17:1 is about the optimum (Walsh and Fletcher, 2004).

A turbo-shaft gas-turbine engine operates much like a turboprop system. It does not drive a propeller; instead, it provides power for a helicopter rotor. The turbo-shaft engine is designed so that the speed of the helicopter rotor is independent of the rotating speed of the gas generator. This permits the rotor speed to be kept constant even when the speed of the generator is varied to regulate the amount of power delivered (Bellis, 2012). A schematic illustration of the simple turbo-shaft engine is shown in Figure 3-1.

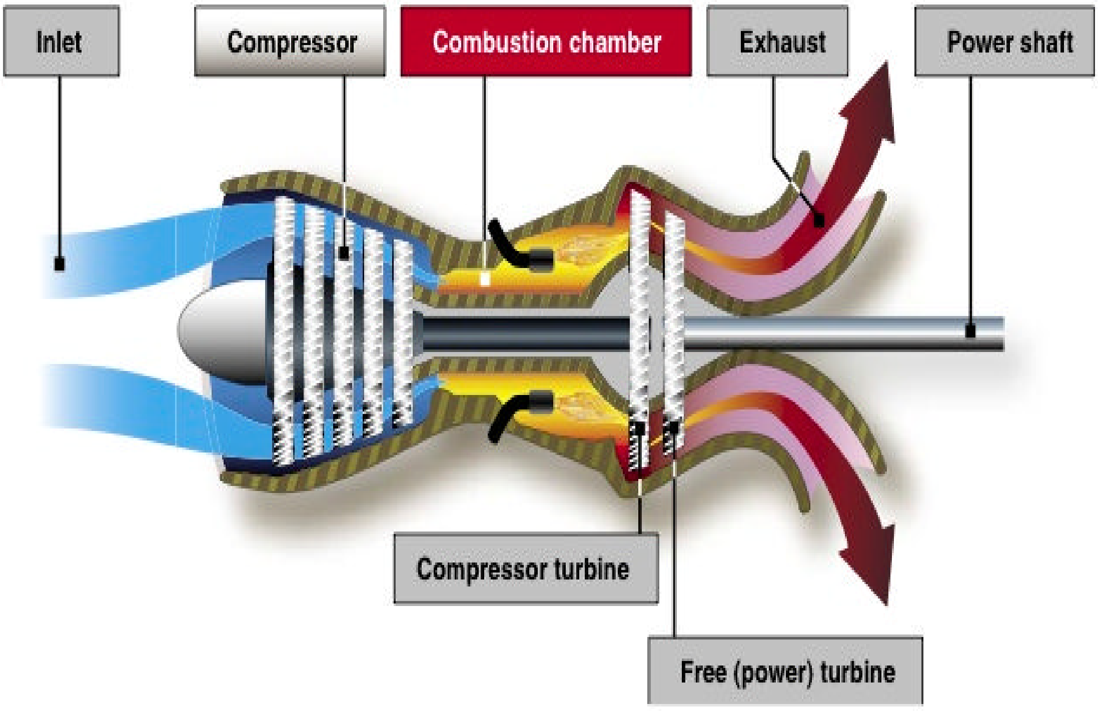

Figure 3-1 Schematic diagram showing the operation of a simplified turbo-shaft Engine (Source: Federal Aviation Administration, USA, AeroManual.com/PHAK)

3.4 Simple cycle two-spool turboshaft engine with free power turbine

In this research, two-spool turboshaft engine with a free power turbine (FPT) is considered as the helicopter engine in which a low pressure compressor (LPC) and a high pressure compressor (HPC) are driven by the high pressure turbine (HPT). The schematic of this engine is shown in Figure 3-2.

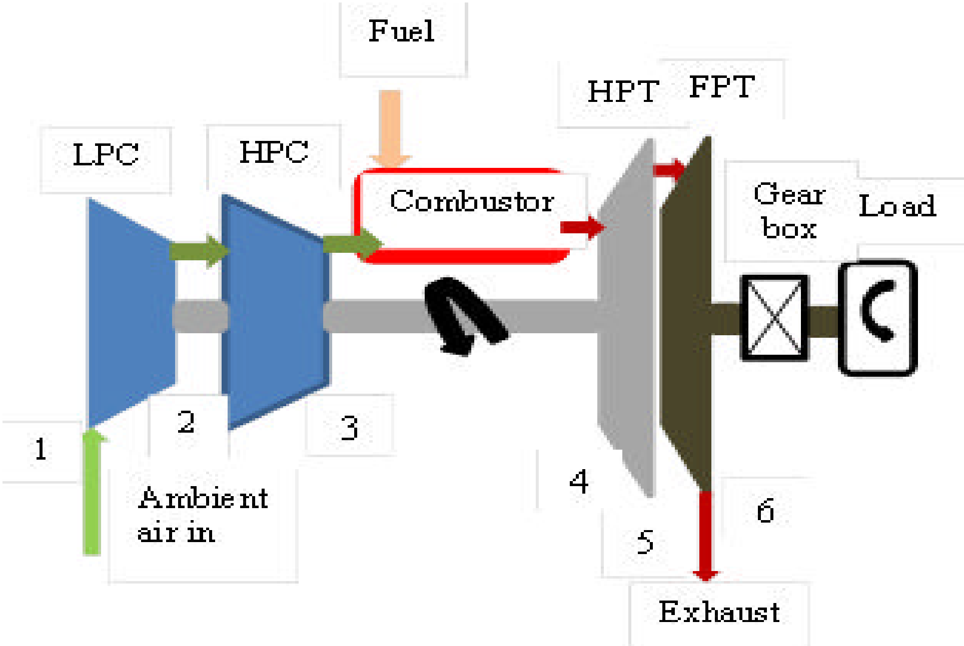

Figure 3-2 **Schematics of simple cycle two-spool turboshaft engine with free power turbine (Nkoi et al, 2013a)**

The T-S diagram of the simple cycle is shown in Figure 3-3 considering isentropic efficiencies of compressors and turbines.

With the notations of Figure 3-2 and Figure 3-3, and applying steady flow energy equation, heat flow into the cycle in the combustion chamber (process 3-4) per unit air mass flow is given by Equation 3-1.

$$q_{in} = h_4 - h_3 = c_p(T_4 - T_3) \qquad \text{Equation 3-1}$$

Heat rejected at constant pressure (process 6-1) in the exhaust is given by Equation 3-2.

$$q_{out} = h_6 - h_1 = c_p(T_6 - T_1) \qquad \text{Equation 3-2}$$

Equation 3-3 gives the total compressor work (CW) (process 1-2-3) per unit air mass flow, where process 1-2 occur in the LPC and process 2-3 occur in the HPC.

$$CW = LPCW + HPCW = (h_2 - h_1) + (h_3 - h_2)$$

$$CW = c_p[(T_2 - T_1) + (T_3 - T_2)] \qquad \text{Equation 3-3}$$

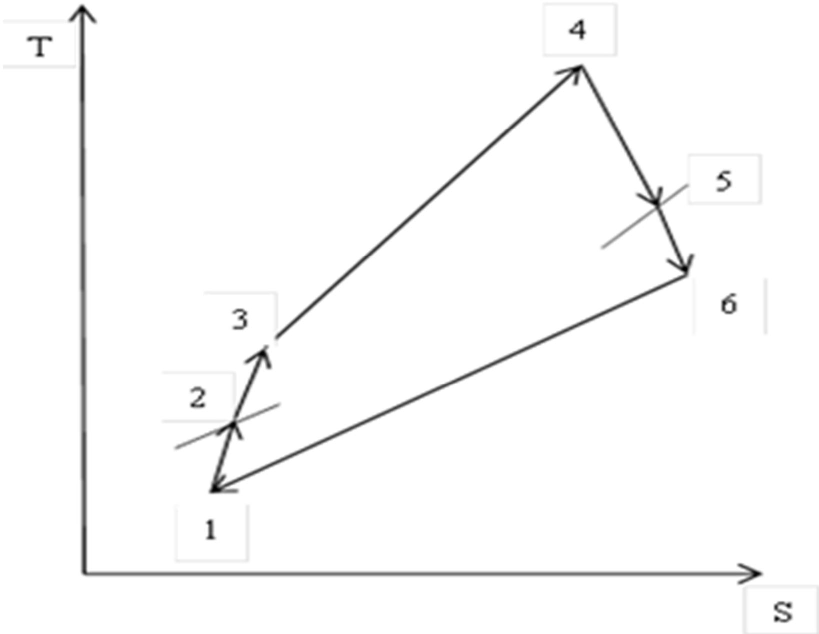

Figure 3-3 T-S diagram of actual simple cycle two-spool engine with free power turbine (Nkoi et al, 2013a)

High pressure turbine work (HPTW) (process 4-5) per unit air mass flow is defined by Equation 3-4.

$$HPTW = h_4 - h_5 = c_p(T_4 - T_5)$$ Equation 3-4

Free power turbine work (FPTW) (process 5-6) given by Equation 3-5

$$FPTW = h_5 - h_6 = c_p(T_5 - T_6)$$ Equation 3-5

This implies that total expansion work (EW) is obtained as stated in Equation 3-6

$$EW = HPTW + FPTW$$

$$EW = c_p[(T_4 - T_5) + (T_5 - T_6)]$$ Equation 3-6

The thermal efficiency is calculated using Equation 3-7 below.

$$\eta_{th} = \frac{useful\ work}{heat\ input} = \frac{EW - CW}{c_p(T_4 - T_3)}$$ Equation 3-7

(Nkoi et al, 2013a).

3.5 Advanced cycles two-spool turboshaft engines with free power turbine

To increase the efficiencies of the simple-cycle, unconventional components are added to the cycle. These components include such like intercooler, regenerator (recuperator), or reheater. However, the initial and maintenance costs of the cycle may increase due to these additional components. The improvements in cycle performance brought about by these components can only be justified if the decrease in fuel costs offsets the increase in other costs. There is the general urge to reduce fuel consumption in gas turbine operation (Lane, 2001). This is achieved by the introduction of these modifications to the simple cycle. The descriptions of these modifications are outlined below.

3.5.1 Recuperated two-spool turboshaft engine with free power turbine

The turboshaft engine described in section 3.4 with a recuperator is represented on the T-S diagram shown in Figure 3-4. The recuperator or regenerator is a heat exchanger connected between the turbine exhaust and the compressor exit. The thermal efficiency of the cycle increases due to recuperation because the portion of heat in the exhaust gases that is supposedly wasted by flaring is now utilised to preheat the air at the exit to the compressor. This, in effect, reduces the heat gain from burning fuel, and hence, decreases fuel consumption for same power output. However, if the compressor outlet temperature is equal or higher than the turbine exhaust temperature, the use of a regenerator is not recommended. Else, there will be a reversal of heat flow to the exhaust gases, causing the efficiency to decrease. Very high pressure ratios in gas-turbine engines could cause this adverse situation, thus recuperation is very useful for small engines.

Referring to the cycle in Figure 3-4, T_6 is the maximum temperature that can occur within the recuperator which is the temperature of the exhaust gases entering the recuperator and leaving the turbine. Air in the regenerator (recuperator) can only be preheated to a temperature below T_6, and air will normally exit the regenerator at T_7, a lower temperature (Saravanamutoo et al, 2009).

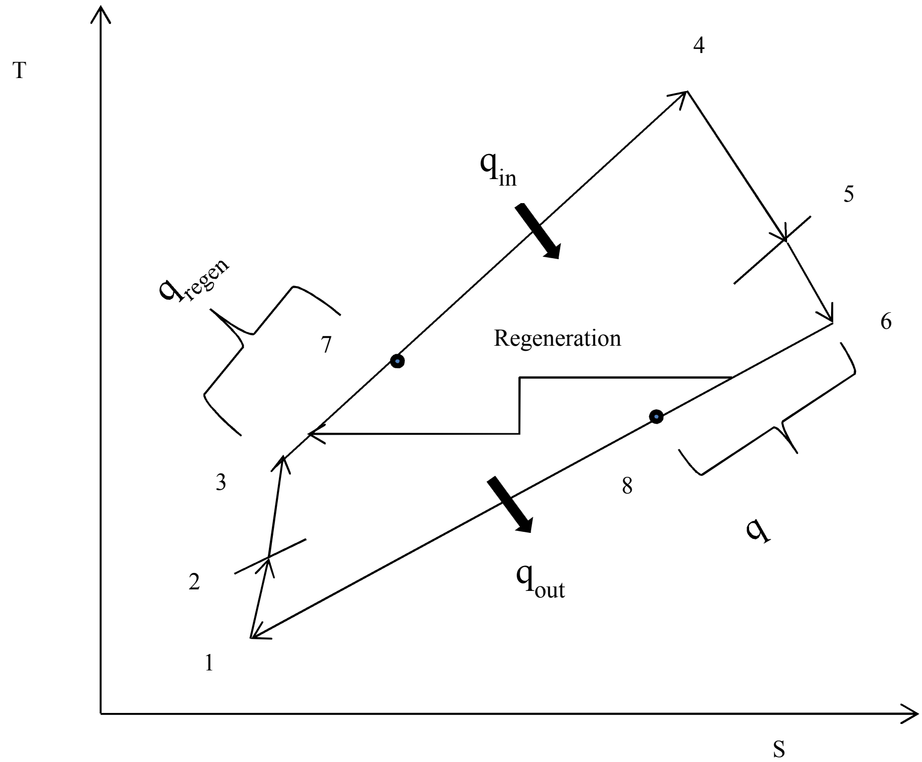

Figure 3-4 T-S diagram of actual recuperated two-spool turboshaft engine with free power turbine (Nkoi et al, 2013a)

The heat input per unit air mass flow here is given by Equation 3-8.

$$q_{in} = h_4 - h_7 = c_p\left(T_4 - T_7\right)$$ Equation 3-8

Equation 3-9 calculates the thermal efficiency in this case making reference to Equation 3-3 and Equation 3-6.

$$\eta_{th} = \frac{useful\, work}{heat\, input} = \frac{EW - CW}{c_p\left(T_4 - T_7\right)}$$ Equation 3-9

(Saravanamutoo et al, 2009; Nkoi et al, 2013a).

3.5.2 Intercooled/recuperated two-spool turboshaft engine with free power turbine

Incorporating an intercooler between the LPC and HPC of the recuperated engine in section 3.5.1 such that air leaving the LPC is cooled before entering the HPC, results in an intercooled/recuperated cycle. Intercooling reduces the total compressor work, thereby, increasing useful work output, turbine work remaining the same (Hartman, 1981). Also, intercooling will increase the specific work of the cycle, increase heat input from combustor, and thus fuel consumption will rise (Ibraham et al, 2010). However, this intercooler effect of reducing thermal efficiency is compensated by recuperation effect in ICR. The T-S diagram for the cycle with both intercooling and recuperation is shown in Figure 3-5, where process 2-3 is intercooling.

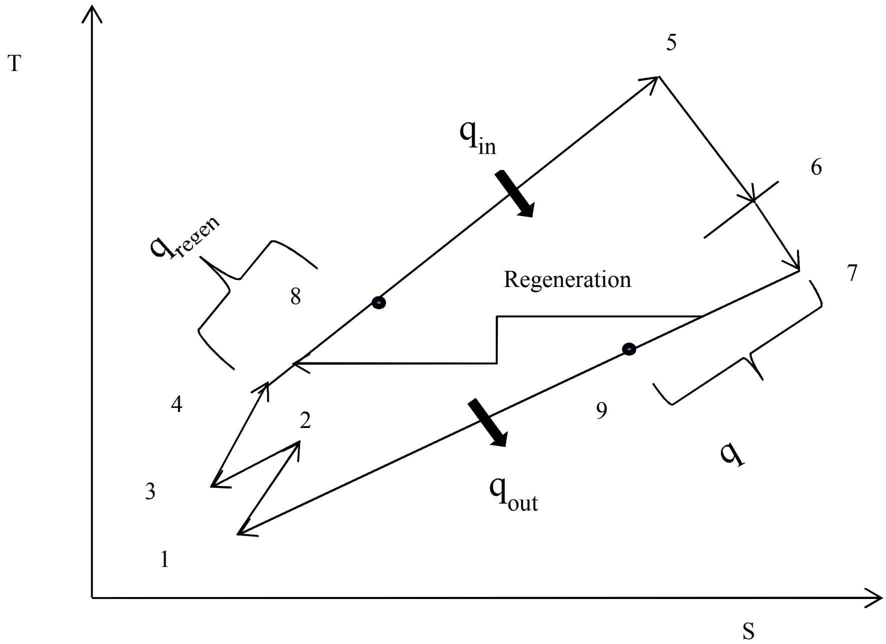

Figure 3-5 T-S diagram of actual intercooled/recuperated two-spool turboshaft engine with free power turbine (Nkoi et al, 2013a)

Using the station numbering and notations in the T-S diagram of Figure 3-5, intercooler effectiveness is given by Equation 3-10 below.

$$\varepsilon_{inter} = \frac{T_2 - T_3}{T_2 - T_1} \qquad \text{Equation 3-10}$$

(Bromnick et al, 1998).

3.6 Helicopter engine model simulation

Performance analysis of a gas turbine engine starts with preliminary design of the engine model. The nature of application, the shaft power requirement, and of course, the class of helicopter, are important factors to be considered when making choice of engine model sizing.

3.6.1 Choice of base-line engine core

Considering an envisaged application scenario for helicopter on mission offshore oil/gas rig, the class of helicopter that would be involved, coupled with availability of data, the choice of engine core for the preliminary helicopter engine model design is made. This core is inspired by Makila 2A model, a Turbomeca turbo-shaft engine. This engine was specially developed to power 11-ton twins, like Eurocopter EC225 and EC725 (Safran Turbomeca). The Turbomeca Makila 2A engine is shown in Figure 3-6 and its schematic diagram is shown in Figure 3-7.

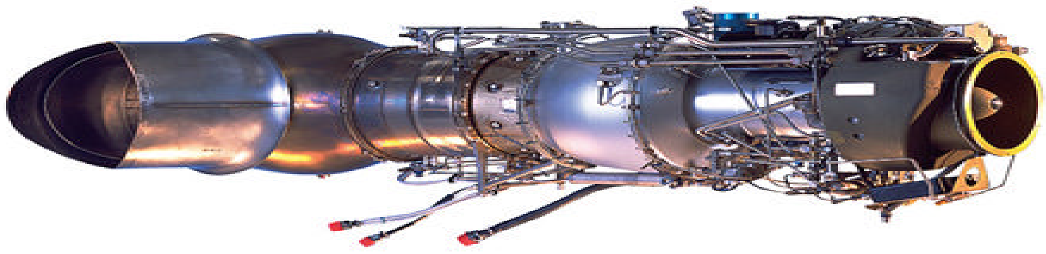

Figure 3-6 Picture of Turbomeca Makila 2A engine (source: Safran Turbomeca)

The Makila 2A is a two-spool turbo-shaft engine with a free power turbine which is capable of delivering 1,567kW (2,101shp) at take-off ISA SLS. Its power output shaft speed is 23000rpm; air mass flow is 5.7kg/s, and pressure ratio of 11:1 (Jane's, 2011; Safran Turbomeca; Turbomeca, 2011).

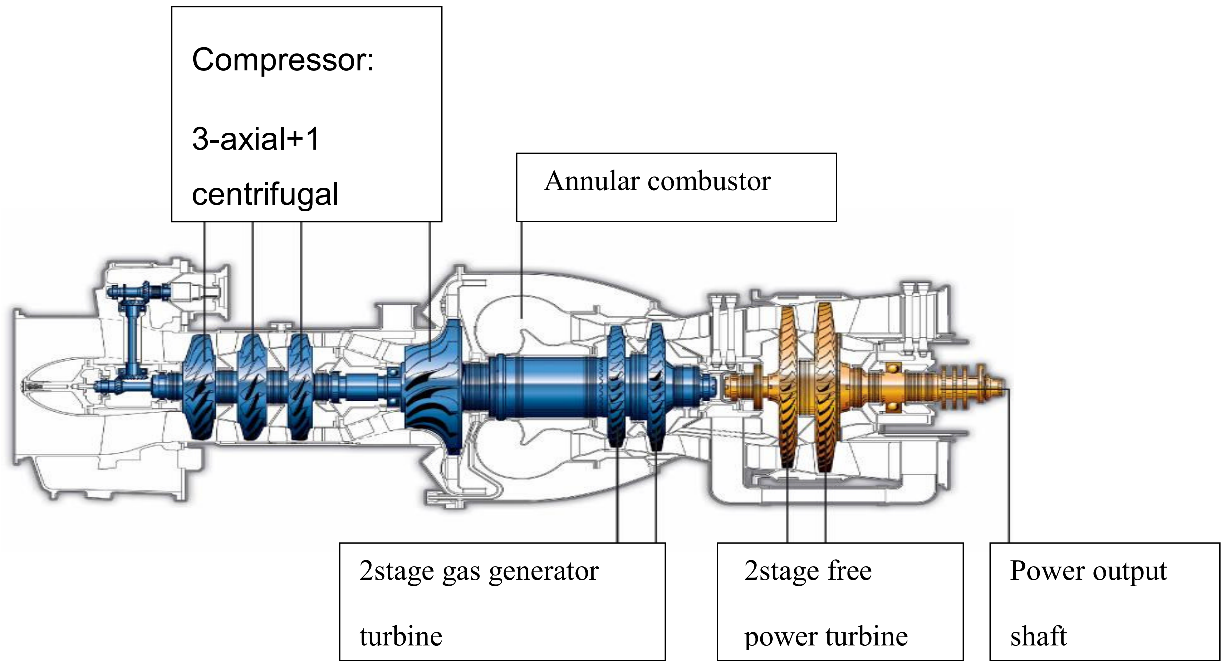

Figure 3-7 schematic diagram of Makila 2A engine (source: Safran Turbomeca)

3.6.2 Simple cycle (baseline) engine design point performance simulation

It should be understood that the design point of the inspiring engine core is proprietary information of the original equipment manufacturer (OEM), and as such, the design point is reasonably chosen by the engineering judgment. This is because some key defining parameters of the DP like the turbine entry temperature (TET), etc. are not usually disclosed by the OEM (Andreadis, 2009). Based on this fact, and due to availability of data, take-off condition at international standard atmosphere, sea level static (ISA SLS) is chosen as the design point with the adoption of U.S.A.F. standard for pressure recovery at intake.

3.6.2.1 TURBOMATCH model of the simple cycle (baseline) engine

In order to carry out computation of the engine performance, the engine components are modelled in TURBOMATCH bricks as described in section 2.8. Following the schematics of the core engine shown in Figure 3-7, the base-line engine components in TURBOMATCH bricks are shown in Figure 3-8 below.

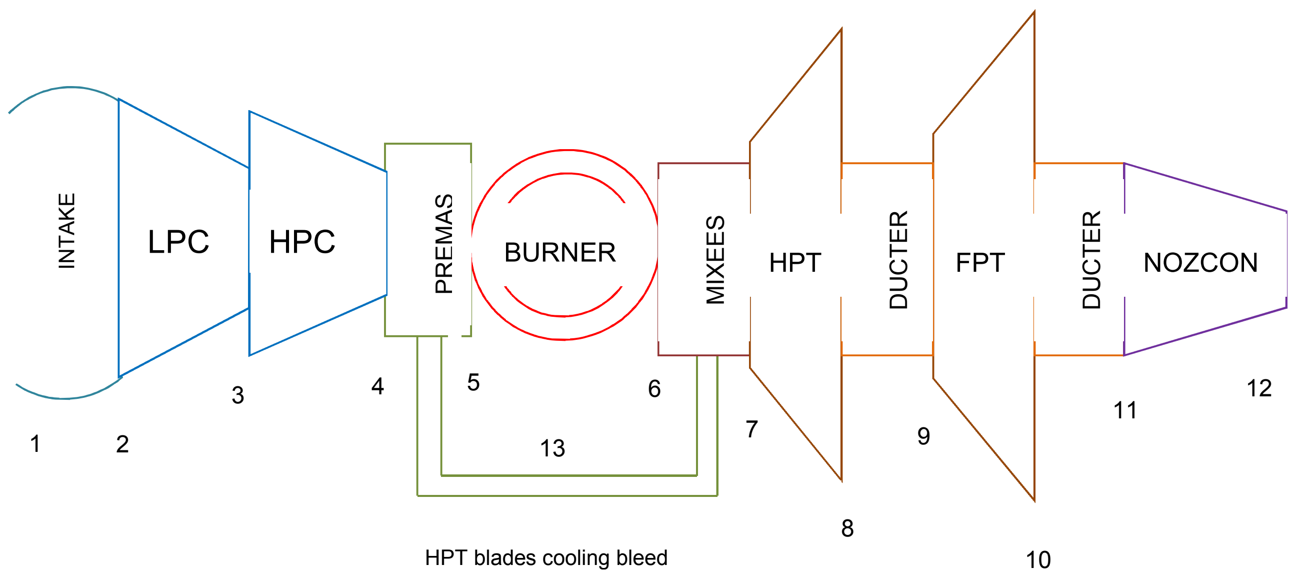

Figure 3-8 Simple cycle 2- spool helicopter engine components in TURBOMATCH bricks (inspired by Turbomeca Makila 2A core)

The component bricks are built in TURBOMATCH code with their respective station numbers, station vectors, and brick data assigned accordingly to form the simulation programme input file. The design parameters of the engine are presented in Table 3-1 below.

Table 3-1 Design parameters of the simple (base engine) cycle

Design parameter	Value
Power rating (Free power turbine)	1567kW
Compressor isentropic efficiencies	0.79
Surge margin parameter	0.85
Overall pressure ratio	11.25
LP compressor pressure ratio	2.5
HP compressor pressure ratio	4.5
Turbine entry temperature	1500K
Inlet air mass flow	5.7kg
Combustor efficiency	0.99
HP turbine isentropic efficiency	0.88
Power turbine isentropic efficiency	0.89

The turbine entry temperature and component efficiencies are assumed. Both compressors are driven by the HP turbine. A 10% air mass flow bleed for cooling of HP turbine blades, and a combustion chamber pressure loss of 5% of the HPC delivery pressure are allowed. The surge margin parameter in Table 3-1 is the factor that limits the compressor operating point from coinciding on the surge line in order to prevent the compressor from surge. In TURBOMATCH code, surge margin parameter lies between 1.00 and zero. Depending on pressure ratios, in TURBOMATCH code, as surge margin tends to the value of 1.00, operating point approaches surge condition and as it tends to zero, operating point approaches choke condition. The surge margin of 0.85 allotted in this design is the default value in TURBOMATCH and means that the operating point is kept literally at a safe distance from the surge line. Surge margin parameter Z is defined by Equation 3-11.

$$Z = \frac{(\pi - \pi_{choke})}{(\pi_{surge} - \pi_{choke})}$$ Equation 3-11

Where, π = pressure ratio at design point, π_{surge} = pressure ratio at surge condition, and π_{choke} = pressure ratio at choke condition (Palmer, 1999).

The simulation is ran in TURBOMATCH, and the output file gives the performance results shown in Table 3-3. The TURBOMATCH simulation input and result file is presented in Appendix A.1

3.6.3 Recuperated helicopter engine DP simulation

Maintaining the baseline engine core arrangement as described in section 3.6.2, a recuperator (a set of heat exchangers) is coupled between the outlet of the power turbine and HP compressor, and modelled in TURBOMATCH bricks shown in Figure 3-9.

The TET, OPR, inlet mass flow, and component efficiencies presented in Table 3-1 are maintained, while additional design parameters for the recuperated engine are shown in Table 3-2.

Table 3-2 Additional design parameters of the recuperated cycle engine

Design parameter	Value
Recuperator effectiveness	65%
Cold side pressure loss	1%
Hot side pressure loss	3%

A bleed of about 7% of inlet air flow for the HP turbine inlet blades cooling, and a mass flow leakage of 0.02kg for the recuperator, are allowed.

Maintaining take-off point at ISA SLS as design point, the engine is simulated in TURBOMATCH codes and output results generated. The DP performance results are summarised in Table 3-3.

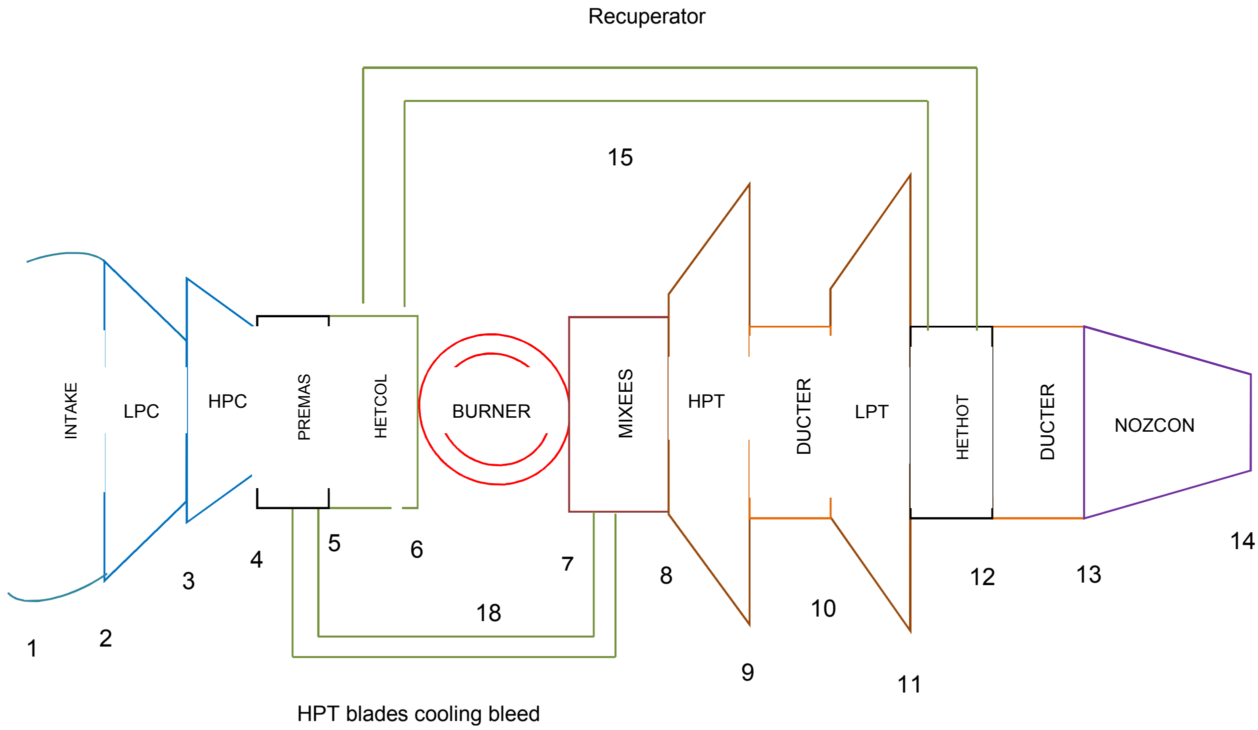

Figure 3-9 Recuperated helicopter engine components in TURBOMATCH bricks.

3.6.4 DP simulation of engine with LP compressor zero-staged

A compression stage is added at the inlet of the LP compressor of the simple cycle-baseline engine thereby modifying it to a different engine configuration. This additional stage (zero stage) increases the overall pressure ratio by 1.13, and is intended to increase air mass flow through the engine. The combination of all the compressors is still driven by the HP turbine. A bleed of about 8% of inlet air mass flow is permitted to cool the HP turbine inlet blades. With the core arrangement of the baseline engine maintained, this zero-staged configuration is modelled in TURBOMATCH bricks shown in Figure 3-10. Keeping TET at 1500K and adopting the component efficiencies of the baseline engine, the engine DP is simulated with take-off at ISA SLS as design point. The performance results are stated in Table 3-3. The TURBOMATCH simulation result file is presented in Appendix A.3

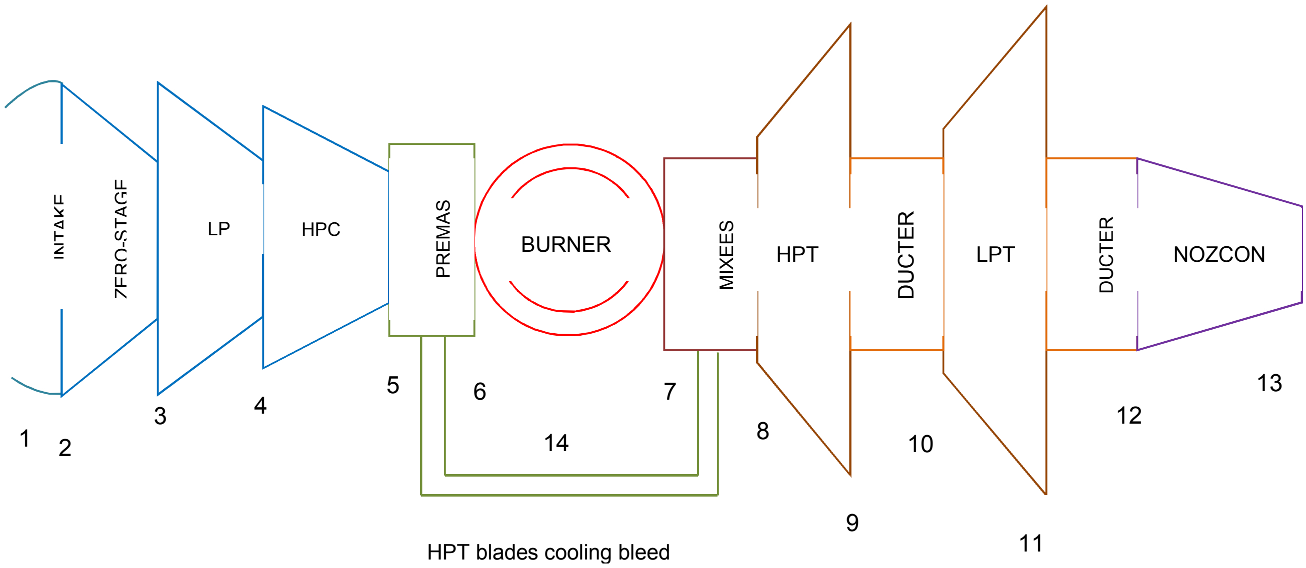

Figure 3-10 Helicopter engine with LP compressor zero-staged in TURBOMATCH bricks with station numbering

3.6.5 Intercooled/recuperated helicopter engine DP simulation

The recuperated engine cycle described in section 3.6.3 is modified by incorporating an intercooler between the LP and HP compressors. This is aimed at lowering the temperature of the air mass entering the HP compressor in order to reduce the work done by the HP compressor, and consequently, the overall compression work is reduced, and as such, cycle efficiency would improve. The parameters of the recuperator cycle are maintained, except that a bleed of 10% of the inlet air mass flow is allowed for HP turbine inlet blade cooling. The air leaving the LP compressor is cooled to a temperature of 300^{o}C which results from an intercooler effectiveness of 88%, and a pressure loss of 4% of LP compressor delivery pressure. Maintaining take-off at ISA SLS as design point the intercooled/recuperated engine is simulated as modelled in TURBOMATCH bricks shown in Figure 3-11 below.

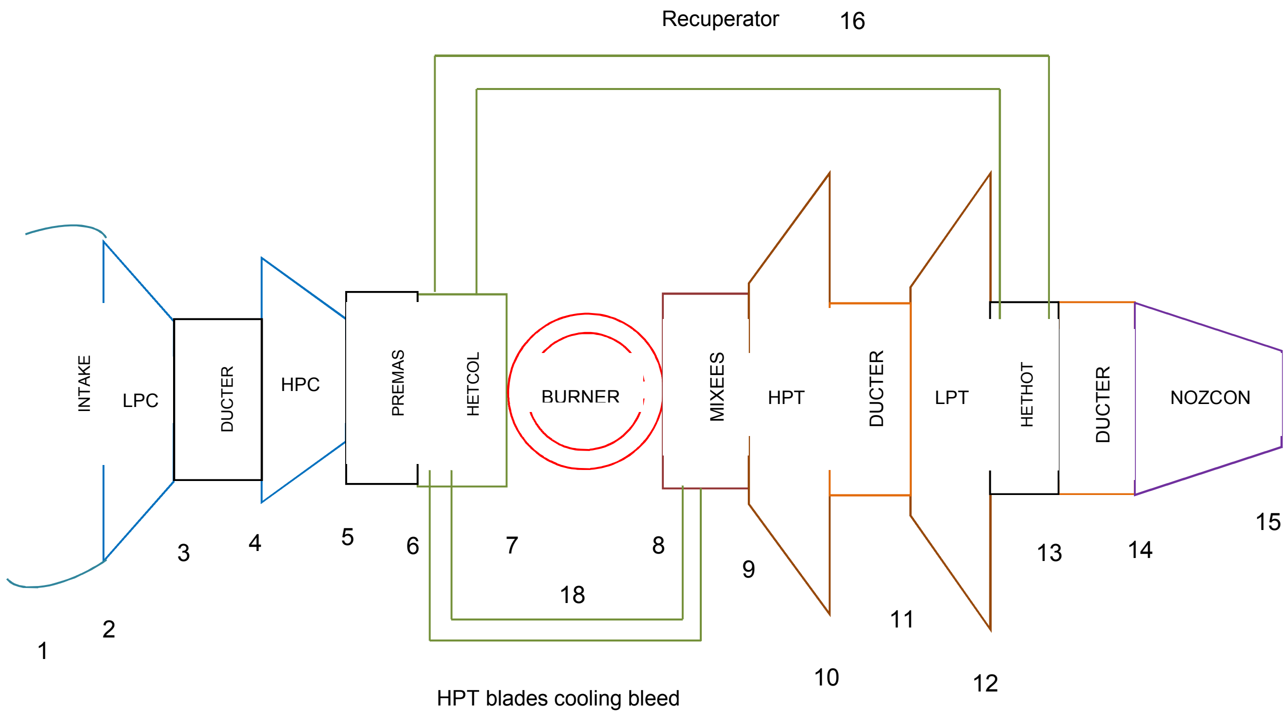

Figure 3-11 ICR helicopter engine components inTURBOMATCH bricks

The DP performance result of the intercooled/recuperated helicopter engine is indicated in Table 3-3 , whereas the simulation result file is shown in Appendix A.2 .

Table 3-3 Summary of DP performance results of helicopter engines simulation

Performance parameter	Value at DP of simulated helicopter turboshaft engines			
	Simple cycle	Recuperated	LP compressor zerostaged	ICR
Power turbine rating	1,567kW	1,567kW	1,567kW	1,567kW
Inlet mass flow	5.7kg/s	5.7kg/s	5.7kg/s	5.7kg/s
Exhaust mass flow	5.83kg/s	5.81kg/s	5.83kg/s	5.80kg/s
Fuel flow	0.130kg/s	0.107kg/s	0.127kg/s	0.104kg/s
Exhaust gas temperature	908K	916K	887K	931K

Performance parameter	Value at DP of simulated helicopter turboshaft engines			
	Simple cycle	Recuperated	LP compressor zerostaged	ICR
Overall pressure ratio	11.25:1	11.25:1	12.71:1	11.25:1
Thermal efficiency	0.281	0.339	0.287	0.349
LPC power (kW)	625	625	727	625
HPC power (kW)	1538	1538	1606	1166
HPT power (kW)	2163	2163	2333	1791
% variation in HPT power of advanced cycles over that of SC	0	0	7.86	-17.2

The variation in compressor work due to zero-staging LPC and intercooled/recuperation is indicated in the values of LPC power and HPC power in Table 3-3 above. The power produced by the HPT changes accordingly to the sum of the compressor powers being the only turbine that drives all the compressors. At DP the free power turbine (FPT) output is assumed fixed for all four cycles and so is not affected by the variation in compressor work because it is not driving any of the compressors. The rational here is to compare performances of cycles with the same nominal power rating in terms of thermal efficiency and fuel consumption. Recuperation alone has no noticeable effect on compressor work. However, all the advanced configurations reduced the fuel flow which eventually reduced heat energy input in combustor and hence increased thermal efficiency

3.6.6 Verification of engine DP performance results

To verify the results of performance parameters for the simulated baseline engine, comparison is made with public domain source reference data of the inspiring Makila 2A engine core. This is shown in .

Table 3-4.

Table 3-4 Verifying result of simulated baseline engine

Performance parameter	Value per engine at take-off condition		variation	Percentage variation
	Inspiring Makila 2A core	simulated baseline engine		
Power turbine rating (kW)	1,567	1,567	0.00	0.00
Inlet mass flow (kg/s)	5.7	5.7	0.00	0.00
Exhaust mass flow (kg/s)	N/A	5.83	-	-
Fuel flow at cruise speed (kg/s)	0.0915	0.0765	0.015	16.4
Exhaust gas temperature(K)	1069	908	161.24	15.1
Overall pressure ratio	11.00:1	11.25:1	-0.25	-2.3
Thermal efficiency	0.300	0.281	0.019	6.3
Turbine entry temperature (K)	N/A	1500	-	-

3.7 Off-design performance results of the helicopter engines

As described in section 2.7, gas turbine engines normally do not operate at the DP in practice due to the effects of conditions such as changing ambient temperature, altitude, turbine entry temperature, among others. By the use of component maps in TURBOMATCH codes, the off-design performance of all the engine versions are simulated and the variation of some key output parameters are plotted in Figure 3-12 to Figure 3-15.

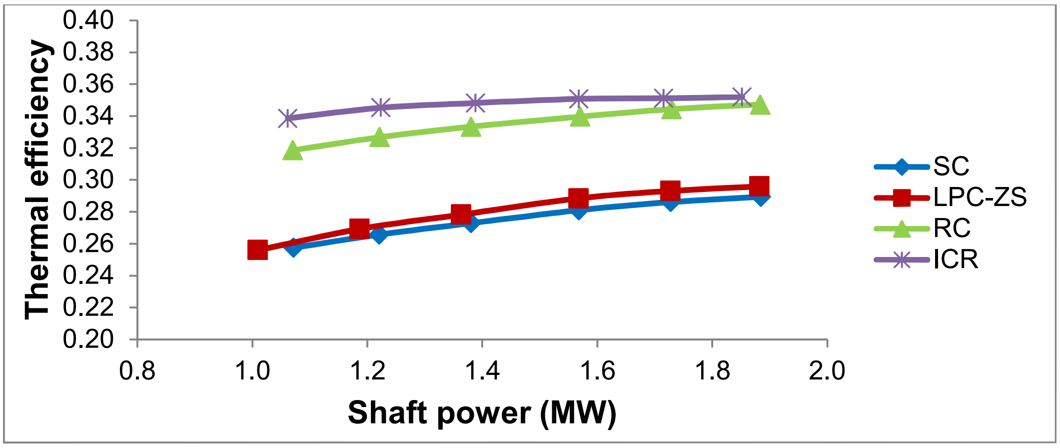

Figure 3-12 Variation of thermal efficiency with shaft power at ISA SLS

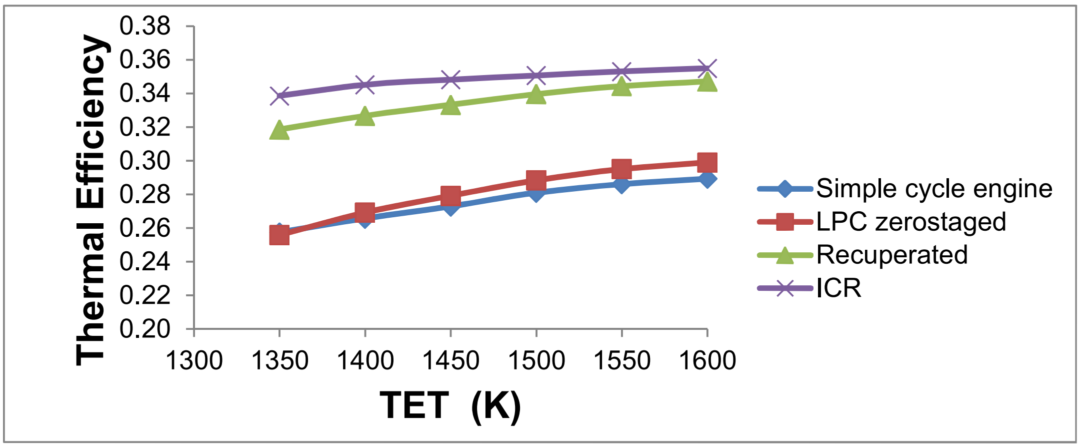

Figure 3-13 Variation of thermal efficiency with TET at ISA SLS

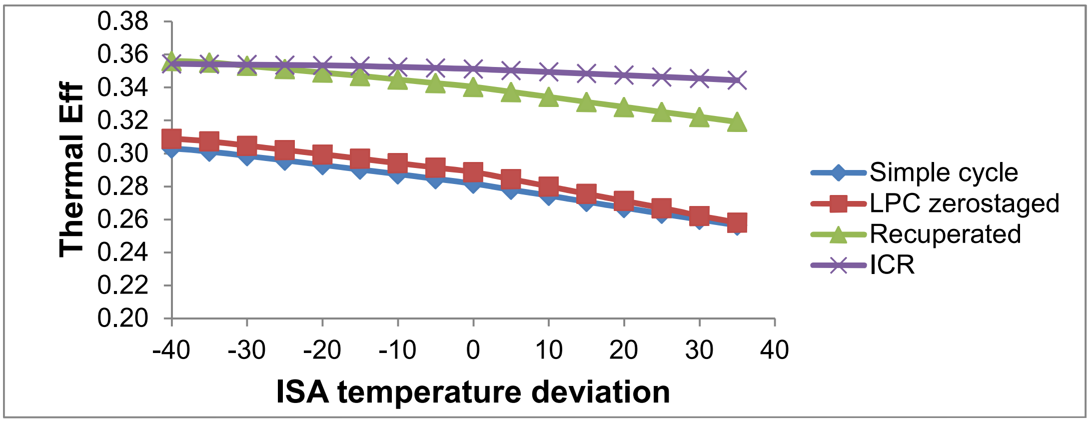

Figure 3-14 Effect of ambient temperature change on thermal efficiency

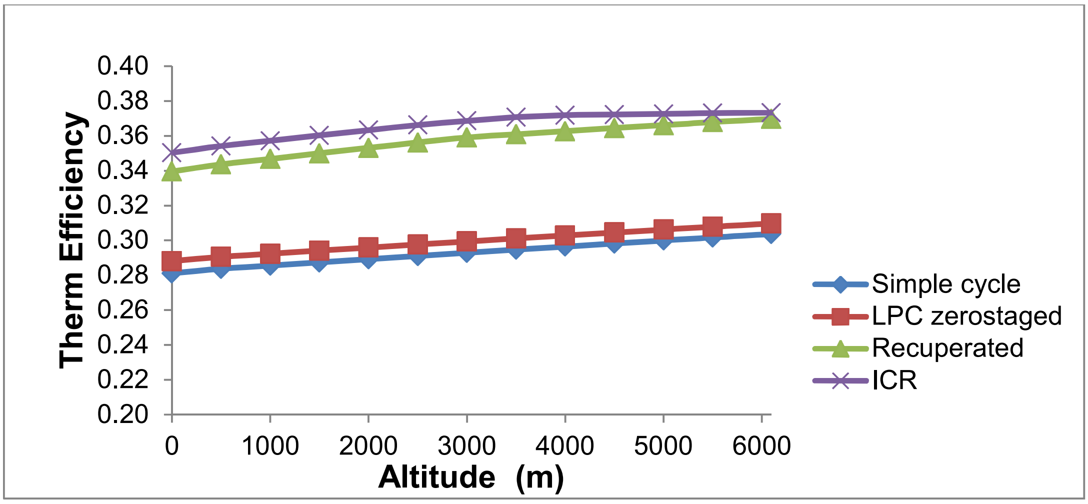

Figure 3-15 Effect of altitude on thermal efficiency at Mach 0.2

From the simulation results shown in Table 3-3 and plots of Figure 3-12 to Figure 3-15 it could be observed that the recuperated, LP compressor zero-staged, and the intercooled/recuperated, engines, all have increased thermal efficiency, compared to the simple cycle – baseline engine at both DP and OD conditions. The percentage increases in thermal efficiency of these advanced cycle engines over the traditional simple cycle engine especially at DP are shown in Figure 3-16. More so, the increase in thermal efficiencies implies that specific fuel consumption is improved in the advanced cycle engines than the simple cycle.

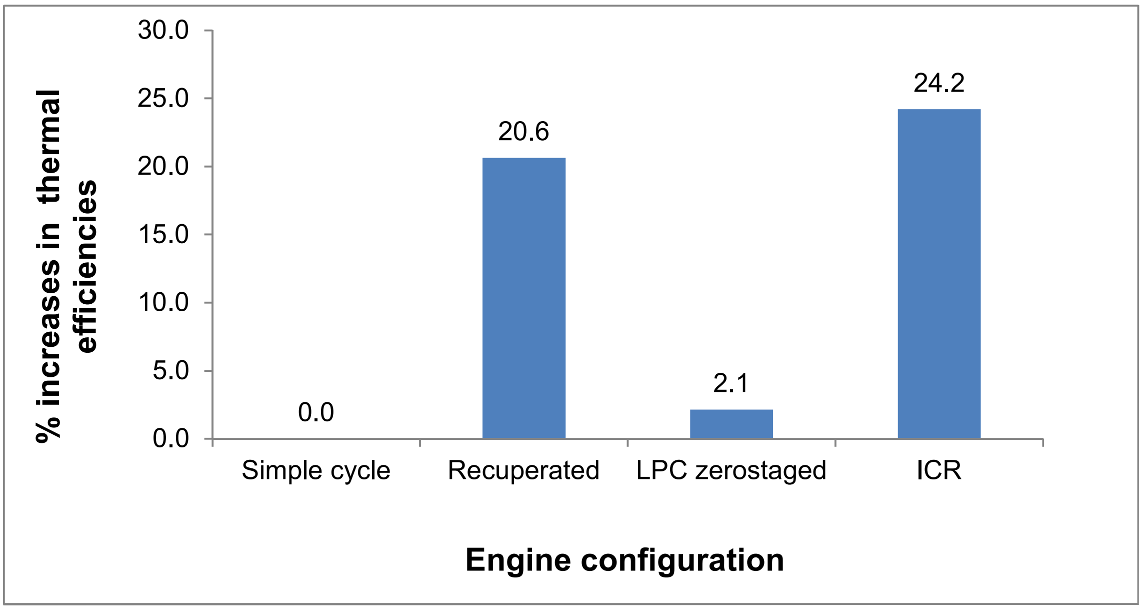

Figure 3-16 percentage increases in thermal efficiencies of advanced cycles over simple cycle.

The advantage of improved performance of the recuperated cycle is as a result of reduction in the heat flow rate required from fuel combustion. This is occasioned by increased temperature of the air stream at the inlet to the combustor by the recuperator, thereby reducing fuel flow. This feature of the recuperator coupled with further reduction in compressor work occasioned by the incorporation of the intercooler makes the ICR cycle to register better performance. The cycle with LPC zero-staged showed a better performance than the simple cycle because of the increase in air mass flow through the engine by the additional stage of compression in front of the LP compressor.

It is observed that to a large extent, the advanced engine cycles exhibit better performances in terms of thermal efficiency and SFC, than the traditional simple cycle engine. The percentage increases in thermal efficiencies of engine cycle with LPC zero-staged, RC engine, and ICR engine cycles, over simple cycle at DP are 2.1%, 20.6%, and 24.2% respectively, whereas percentage reduction in SFC in these cycles over simple cycle at DP are 2.6%, 17.3%, and 21.1% respectively.

However, it is important to note that though the thermal efficiency is improved by using the advanced cycles, the incorporation of intercooler, recuperators, and additional compression stage, would render the engine more complex. This would raise the capital and maintenance cost actually, but cost of fuel would reduce due to reduction in fuel consumption.

These results compare favourably with values obtained in the literature. For instance, it was reported that the 1.4MW ICR Heron-1 turbo-shaft gas turbine manufactured by EECT of the Netherland, exhibits thermal efficiency of 42.9% while a simple cycle gas turbine of same power range has thermal efficiency of about 26 - 34%. This represents a thermal efficiency increase of about 26.2% at the minimum (Farmer, 2002). More so, zero-staging the LP compressor of a helicopter turbo-shaft engine of the RTM322 core was reported to have yielded 5.21% increase in thermal efficiency over that of the base-line engine (Vickers, 1995; Nkoi et al, 2013a).

3.8 Chapter summary

The following are described in this chapter:

- The definition of a helicopter is given stating its features, functions, and various areas of application.
- A helicopter engine is defined as the turbo-shaft gas turbine with a view of its two-spool configuration. Simple and advanced cycle two-spool with free power turbine arrangement are discussed stating the underlying thermodynamic principles.

- Helicopter engine model performance simulation is carried out in TURBOMATCH with an engine core inspired by Turbomeca makila 2A core – a simple two-spool turbo-shaft with free power turbine. Performance simulations of its advanced cycles (RC, ICR, and LPC zero-staged) are also done.
- Verification of the simple (base) engine is done by comparing simulated performance parameters with values of the inspiring makila 2A core obtained in the literatures.
- Off-design performance simulations of the four cycle options are carried out with respect to changing TET, and ambient temperature at ISA SLS, and changing altitudes (at Mach 0.2). The engines performances in terms of SFC and thermal efficiency are noted and compared.
- It is observed that all three advanced cycles show superior performance than the simple base engine cycle. It is worth noting that the additional components would actually increase the capital/installation cost of the advanced cycles than that of the simple cycle.
- The results obtained compared favourably with trends in the literatures.

4 PART B: AERO-DERIVATIVE INDUSTRIAL GAS TURBINES (ADIGT) PERFORMANCE ANALYSIS

4.1 Overview

Same methodology of applying gas turbine engine performance code - TURBOMATCH used in chapter 3 is adopted in this chapter to analyse the technical performances of two categories of aero-derivative industrial gas turbines (ADIGT) that would subsequently be used in petrochemical industry CHP. These categories of ADIGT are small-scale (SS) ADIGT, and large-scale (LS) ADIGT. The chapter begins with presenting the conversion of the helicopter gas turbines discussed in part A to simple and advanced cycles SS ADIGT and their performances are analysed. Similarly, the performances of simple and advanced cycles large-scale ADIGT are also analysed.

In Addition, the method of applying gas turbine engines emissions prediction code – HEPHAESTUS is adopted to estimate NO_x, CO, CO_2, and $H_2O_{(vapour)}$ emissions indices of the two categories of ADIGT. HEPHAESTUS code has been described in section 2.9.3.

4.2 Features of ADIGT

As the name implies, aero-derivative industrial gas turbines (ADIGT) are gas turbines derived from aero-gas turbine engines by means of conversion. The decision to use aero-derivative gas turbines is mainly based on economical and operational advantages. Gas turbine manufacturers have found that to reduce cost of designing and developing new gas turbines, a more effective approach is to develop high performance industrial gas turbines by modifying aircraft gas turbine engines (Bhargava et al, 2004). Also, by introducing aero-derivative's removable gas generator, better flexibility is provided which in turn led to reducing maintenance operation and enhancing gas turbine availability in industrial applications (Najjar, 2000). More so, implementing aero-derivative technology for industrial gas turbine has resulted in low maintenance downtime, good part-load efficiencies, and higher rate of return (Yang, 1997).

More so, aero-derivative gas turbines can meet stringent NOx control requirements because they are suitable for power augmentation by steam injection. For instance, the GE LM series industrial aero-derivative gas turbines are meeting NOx requirements as low as 25 parts per million (ppm) using steam injection. Other merits of aero-derivative gas turbines include low weight-to-power ratio, compactness, and hence, lesser erection and startup time (Keller and Studniarz, 1987; Roy, 2012). More so, aero-derivative gas turbine are most suitable for highly efficient cogeneration plants, more flexible combined-cycle plants, and in mechanical drive applications for production and distribution of oil and gas (Doom, 2013).

Modern aero-derivative gas turbine drivers will feature a new generation of offshore or onshore-emergency power generation trains, and would be attractive options for offshore, floating or fast-response emergency power trains. The efficiency of aero-derivative gas turbines is typically around 40 - 45% compared to 30 - 35% for heavy duty industrial gas turbines (Almasi, 2012).

4.3 Categories of ADIGT

Based on different ranges of power ratings, ADIGT engines could be grouped into three categories, namely, small-scale, medium-scale, and large-scale ADIGT engines. Small-scale ADIGT category can be defined as having the range of power rating from about 0.6MW up to 5MW. The range of power rating greater than 5MW but up to 20MW could be classified as medium-scale category. Large-scale category would be considered as the class having power rating above 20MW (Major and Powers,1999; Energy and Environmental Analysis, 2008). As stated in section 4.1, only the small-scale and large-scale classes of ADIGT engines are considered to be analysed in this research.

4.3.1 Small-scale (SS) ADIGT engines (helicopter engines derivatives)

The small-scale (SS) ADIGT engines are thought of to emanate from the conversion of the helicopter engines earlier discussed in chapter 3, to industrial configuration having low power rating in the vicinity of 2MW. In this category, the simple cycle helicopter engine inspired by Makila 2A core is chosen and earmarked as the parent baseline engine to be converted to small-scale ADIGT engine.

4.3.1.1 DP performance of simple cycle two-spool SS-ADIGT engine

The simple cycle SS-ADIGT baseline engine components in TURBOMATCH bricks is the same as that of the helicopter turboshaft engine shown in Figure 3-8 in section 3.6.2.1. However, as typical of conversion to aero-derivative industrial gas turbines, the following changes are made to the engine and component parameters. Pressure recovery at the intake is set to 0.9951, with compressor surge margin increased by 0.05. Compressor isentropic efficiencies are reduced to 0.78, whereas HP and LP turbine isentropic efficiencies are decreased to 0.87 and 0.88 respectively. The corrected rotational speed of the compressors are reduced to 0.8, and the inlet mass flow reduced to 5.53kg/s with a 9% bleed for HP turbine inlet blade cooling. Maintaining the TET at 1500K, and ISA SLS as the design point, the engine was simulated in

TURBOMATCH codes and the DP performance result generated. A summary of the performance is shown in Table 4-1

4.3.1.2 DP simulation of recuperated SS-ADIGT engine

A recuperator is added after the LP power turbine of the simple SS-ADIGT engine described in section 4.3.1.1, while retaining component efficiencies, TET and inlet mass flow. The effectiveness of the recuperator is 55% and its allowable mass leakage is 2%. The cold side and hot side pressure losses are 3% each. However, a mass bleed of 7.5% of intake air mass flow is channeled for HPT inlet blade cooling. This engine was simulated for DP performance and a summary of the result is shown in Table 4-1

4.3.1.3 DP performance of ICR SS-ADIGT engine

The ICR SS-ADIGT engine components in TURBOMATCH bricks is the same as that of the helicopter turbo-shaft engine shown in Figure 3-11 of section 3.6.5. The core engine parameters of the recuperated SS-ADIGT are retained except for the inclusion of an intercooler of 40% effectiveness, with pressure loss of 4% of LPC delivery pressure. The air leaving the LP compressor is cooled to a temperature of 300^{o}C. Of the inlet mass flow, an allowable 20% bleed for HPT inlet blade cooling is made. Also, keeping ISA SLS as design point, the engine was simulated and the summary of its DP performance shown in Table 4-1 below. The simulation result file is presented in Appendix B.1 .

Table 4-1 Summary of DP performance results of SS-ADIGT engines simulation

Performance parameter	Value at DP of simulated two-spool SS-ADIGT engines		
	Simple cycle	Recuperated	ICR
Power turbine rating (kW)	1,567	1,567	1,567
Inlet mass flow (kg/s)	5.53	5.53	5.53
Exhaust mass flow (kg/s)	5.653	5.638	5.637
Fuel flow (kg/s)	0.125	0.108	0.107
Exhaust gas temperature (K)	890	900	826
Overall compression pressure ratio	11.25:1	11.25:1	11.25:1
Thermal efficiency	0.296	0.336	0.339

4.3.2 Off-design performance results of SS-ADIGT engines

Gas turbine engines normally do not operate at the DP in practice due to the effects of conditions such as changing ambient temperature, altitude, turbine entry temperature, among others. By the use of component maps in TURBOMATCH codes, the off-design performances of the SS-ADIGT engines were simulated and the variation of some key engine output parameters were plotted and presented in Figure 4-1 to Figure 4-3 .

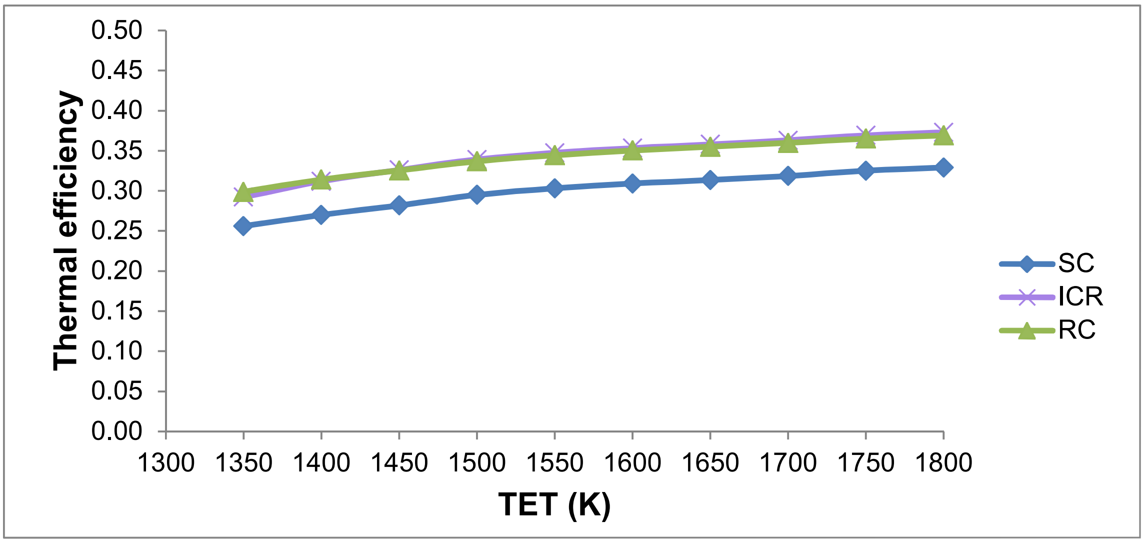

Figure 4-1 Variation of thermal efficiency with TET at ISA SLS (SS-ADIGT)

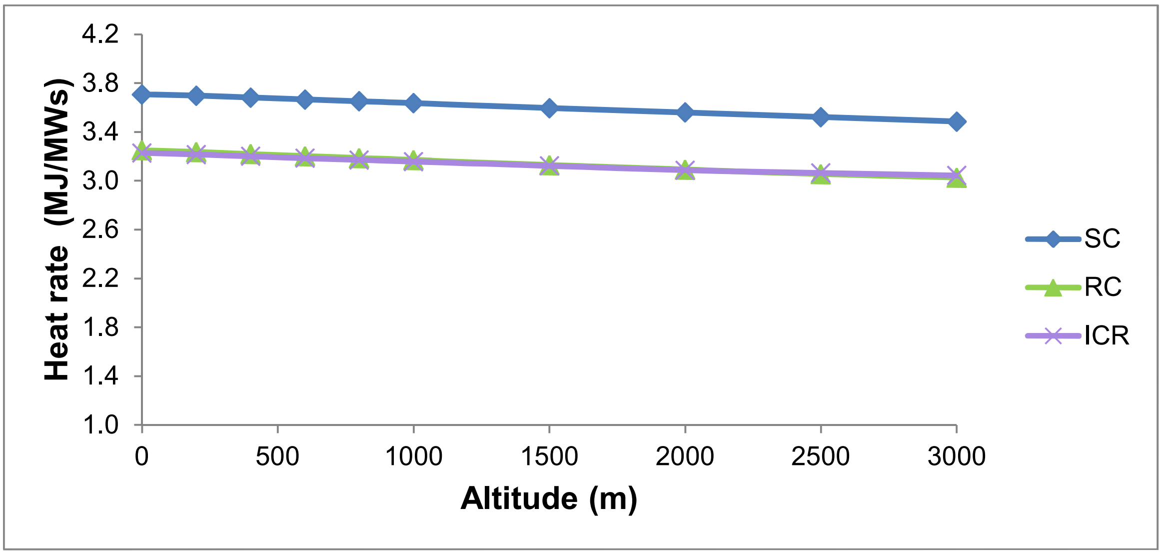

Figure 4-2 Effect of altitude on heat rate (SS-ADIGT)

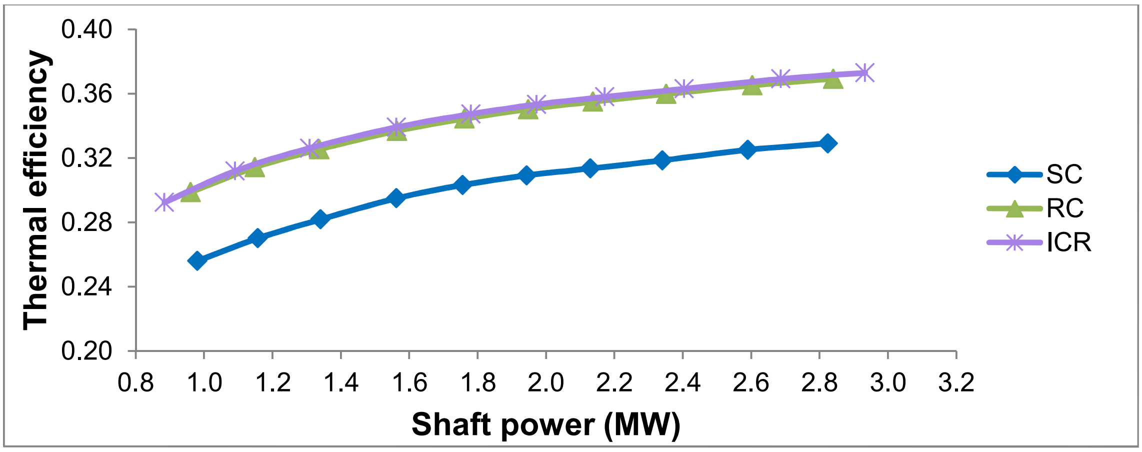

Figure 4-3 Variation of thermal efficiency with shaft power at ISA SLS (SS-ADIGT)

With reference to the simulation results shown in Table 4-1, and plots of Figure 4-1 to Figure 4-3, it could be observed that for the SS-ADIGT engines, the RC, and ICR, engines have increased thermal efficiency, compared to the SC engine at both DP and OD. This is due to the fact that the intercooler decreases the temperature of the air entering the HP compressor and as such reduces the HP compressor work. Similarly, the recuperator increases the temperature of air entering the combustor to reduce the quantity of heat flow required from burning fuel by heat-exchange action with stream of exhaust gas. The ICR cycle combines both advantages of intercooling and heat-exchange discussed above to achieve increased thermal efficiency. Similarly, heat rate is reduced in the advanced cycles compared to the simple cycle

In Figure 4-4, the percentage increases at DP in thermal efficiency of the advanced cycle engines over the simple cycle engine are shown.

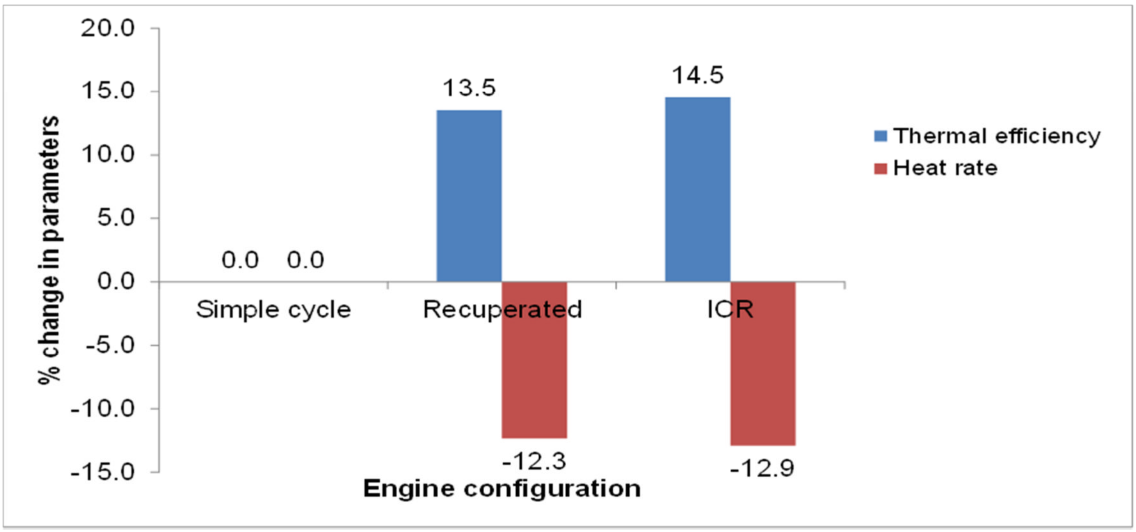

Figure 4-4 Percentage change in performance parameters of RC and ICR cycles over simple cycle for the SS-ADIGT

The negative sign on the heat rates in the figures above indicate percentage reduction in heat rate of advanced cycles over simple cycle. Of-course increase in thermal efficiency is accompanied with corresponding decrease in heat rate for the ADIGT engines

4.3.3 Large-scale (LS) ADIGT engines

In this category of aero-derivative engines, two representative engine models are considered, which are labelled large-scale-class-1 (LS1) ADIGT, and large-scale-class-2 (LS2) ADIGT engines.

4.3.3.1 Large-scale-class-1 (LS1) ADIGT engine

For this model of large-scale ADIGT, a simple cycle two-spool engine inspired by the aero-derivative GE LM6000-PD core was chosen as the baseline engine. The LM6000 turbine is pictorially shown in Figure 4-5 and consists of a five-stage LPC; a 14-stage HPC with an overall compression ratio of 28.5:1; an annular combustor with 30 individually replaceable fuel nozzles; a two-stage air-cooled HPT; and a five-stage LPT. The LM6000 PD is a dual-rotor “direct drive” gas turbine, derived from the CF6-80C2, high-bypass turbofan aircraft engine, having no free power turbine. The LM6000 utilises the low pressure rotor operating speed of about 3600 rpm of its parent aircraft engine. The LPT rotor drives the LPC and the load while the HPT rotor drives the HPC. The engine has the option of either cold end or hot end drive configuration (Badeer and Evendale, 2000; GE Energy, 2012).

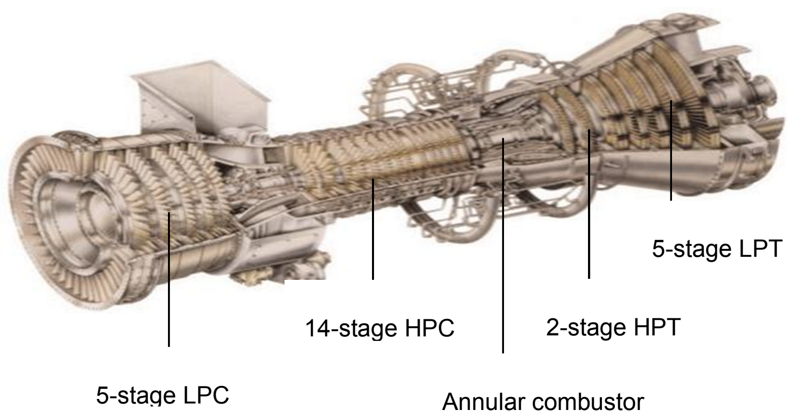

Figure 4-5 Picture of GE LM6000 PD aero-derivative engine (Badeer and Evendale, 2000)

4.3.3.1.1 DP performance of simple two-spool LS1-ADIGT engine

The engine components are modelled in TURBOMATCH bricks shown in Figure 4-6. ISA SLS condition of 43,850kW output power is chosen as the DP with

0.9951 pressure recovery at intake. Assumption is made of the isentropic efficiencies of both the low pressure (LP) axial compressor and high pressure (HP) centrifugal compressor to be 0.88, with a surge margin of 0.80.

Maintaining an overall pressure ratio of about 29.04:1 for the engine, the design pressure ratios of the LPC and HPC are 2.42 and 12.0 respectively, while LPC is driven by LP spool of the LPT and the HPC is driven by the HP spool of the HPT. The turbine entry temperature, being an exclusive reserve of the OEM is assumed to be 1550K and earmarked as the engine handle for the simulation, while the air mass flow is set at 125.0kg/s with a total of 11.3% mass bleed for cooling of both HP and LP turbine inlet blades. An assumed combustor efficiency of 0.99 is made with a combustion chamber pressure loss of 5% of the HPC delivery pressure. The isentropic efficiency of the compressor turbine is taken to be 0.88 while that of the LP power turbine is set at 0.89. Using a default non-dimensional speed of 0.6, and a non-dimensional mass flow of 0.8, the simulation was run in TURBOMATCH codes. The generated DP performance results are summarised in Table 4-2.

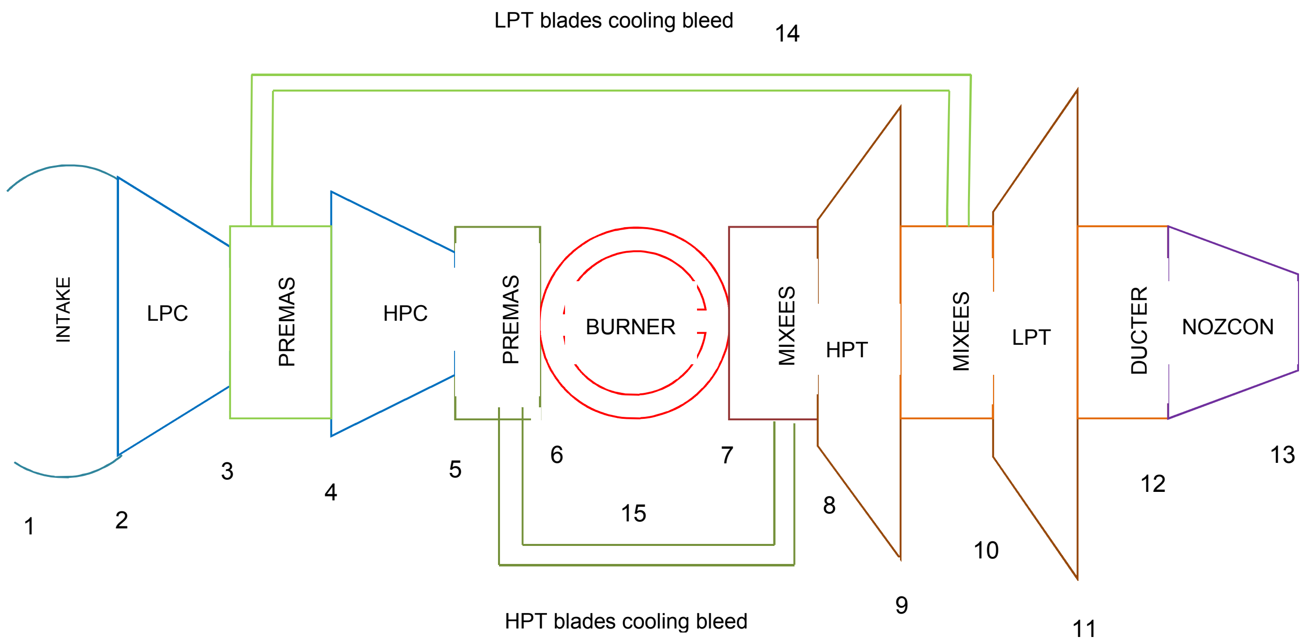

Figure 4-6 Simple cycle 2-spool LS1-ADIGT engine components in TURBOMATCH bricks (inspired by GE LM6000 core)

4.3.3.1.2 DP performance of Intercooled two-spool LS1-ADIGT engine

An intercooler is added between the LP and HP compressors of the simple cycle LS1-ADIGT engine described in section 4.3.3.1.1. While retaining component efficiencies, TET and inlet mass flow, the air leaving the LP compressor is cooled to a temperature of 300^{o}C, with intercooler effectiveness of 40%, and intercooler pressure loss of 4% of LPC delivery pressure. However, a mass bleed totaling about 30% of intake air mass flow is channeled for both HPT and LPT inlet blades cooling. The intercooled (IC) engine components in TURBOMATCH bricks is shown in Figure 4-7, while the DP performance result is summarized in Table 4-2.

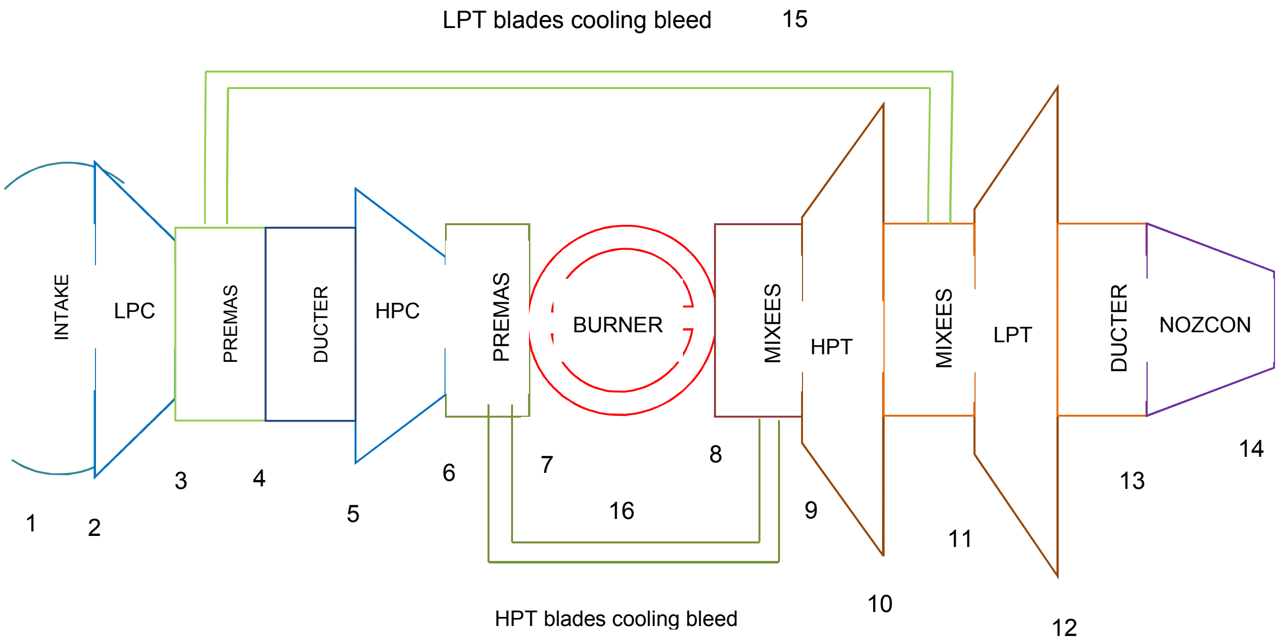

Figure 4-7 Intercooled 2-spool LS1-ADIGT engine components in TURBOMATCH bricks with station numbering

4.3.3.1.3 DP performance of ICR two-spool LS1-ADIGT engine

The ICR two-spool large-scale-1 aero-derivative engine components in TURBOMATCH bricks is shown in

Figure 4-8. The core engine parameters of the intercooled LS1-ADIGT engine described in section 4.3.3.1.2 are retained except for the inclusion of a recuperator of 65% effectiveness, with cold side and hot side pressure losses of 2% and 3% respectively, of the inlet pressure, and 2% mass leakage. The inlet mass flow is 125.0kg/s with a total of 29% bleed for both HPT and LPT inlet blades cooling. Also, keeping ISA SLS as design point, the engine was simulated and the summary of its DP performance shown in Table 4-2.

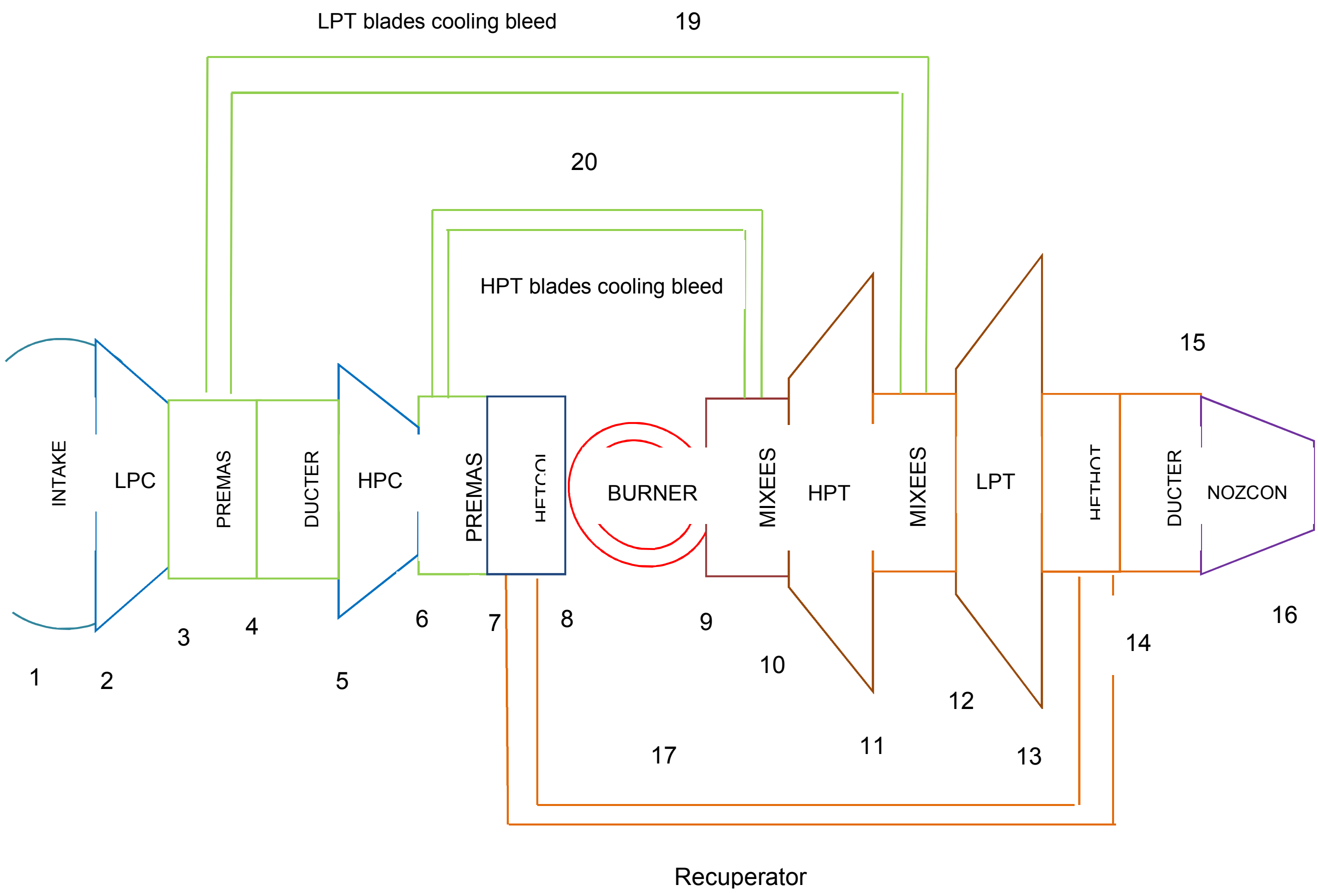

Figure 4-8 ICR LS1-ADIGT engine in TURBOMATCH bricks

Table 4-2 Summary of DP performance results of the LS1-ADIGT engines

Performance parameter	Value at DP of simulated two-spool LS1-ADIGT engines		
	Simple cycle	Intercooled	ICR
Power turbine rating (kW)	43,850	43,850	43,850
Inlet mass flow (kg/s)	125	125	125
Exhaust mass flow (kg/s)	127.5	127.4	127.4
Fuel flow (kg/s)	2.49	2.42	2.42
Exhaust gas temperature (K)	743	657	665
Overall pressure ratio	29.04:1	29.04:1	29.04:1
Thermal efficiency	0.410	0.419	0.420

4.3.3.1.4 Verification of performance results of base engine LS1-ADIGT

To verify the results of performance parameters for the simulated baseline engine, comparison is made with public domain source reference data of LM6000. This is shown in Table 4-3.

Table 4-3 Verifying results of simulated LS1-ADIGT engine

Performance parameter	Value at ISA SLS			
	Inspiring core LM6000	Simulated baseline engine	Variation	% variation
Power turbine rating	43,850kW	43,850kW	0.0	0.0
Inlet mass flow	125kg/s	125kg/s	0.0	0.0
Fuel flow	N/A	2.49kg/s	-	-
Exhaust gas temperature	728K	743K	-15	-2.01
Overall pressure ratio	28.50:1	29.04:1	-0.54	-1.9
Thermal efficiency	0.420	0.410	0.010	2.4
TET	N/A	1550K	-	-

4.3.3.2 Large-scale-class-2 (LS2) ADIGT engines

For this model, a simple cycle three-spool engine inspired by the aero-derivative GE LMS100 core is chosen as the baseline engine. The LMS100 turbine is quite similar in configuration as the LM6000 except that it has a free power turbine (LPT), an intermediary turbine (IPT) that drives the LPC, and an intercooler. With an overall compression ratio of 42:1, it has an annular combustor equipped with dry low emission (DLE) technology, and an air-cooled HPT which drives the HPC. The LMS100 was derived from the LM6000 by the addition of the intercooler and free power turbine delivering an output power of 100MW (GE Energy, 2012).

4.3.3.2.1 DP performance of SC three-spool LS2-ADIGT engine

The engine components are modelled in TURBOMATCH bricks shown in Figure 4-9. The DP is chosen as ISA SLS condition of 100,000kW output power with pressure recovery of 0.9951 at intake. The isentropic efficiencies of both the LPC and HPC are assumed to be 0.875, with a surge margin of 0.80. The design pressure ratios of the LPC and HPC are 3.0 and 14.05 respectively, giving an overall pressure ratio of about 42.15:1. The LPC is driven by LP spool of the IPT and the HPC is driven by the HP spool of the HPT. The turbine entry temperature is assumed to be 1730K and taken as the engine handle for the simulation, while the air mass flow is set at 215.5kg/s with 8.0% mass bleed for cooling of the compressor turbines inlet blades. A combustion chamber pressure loss of 5% of the HPC delivery pressure is allowed whereas the combustor efficiency of 0.998 is assumed. The isentropic efficiency of the HPT and the IPT are taken to be 0.89, and that of the free power turbine is set at 0.90. Default non-dimensional speed of 0.6, and a non-dimensional mass flow of 0.8, are used. The simulation results were generated, and summarised in Table 4-4.

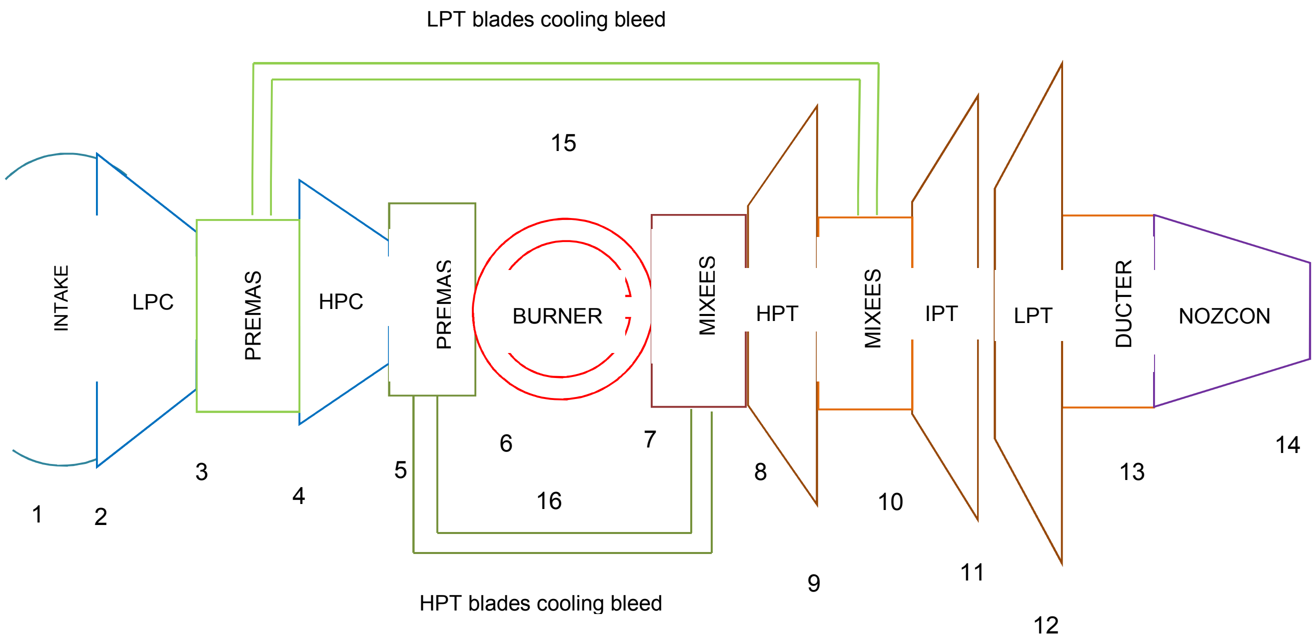

Figure 4-9 Simple cycle 3-spool LS2-ADIGT engine components in TURBOMATCH bricks (inspired by GE LMS100 core)

4.3.3.2.2 DP performance of IC three-spool LS2-ADIGT engine

The simple cycle LS2-ADIGT engine described in section 4.3.3.2.1 is modified by introducing an intercooler between the LP and HP compressors. While retaining component efficiencies, TET, and inlet mass flow, the air leaving the LP compressor is cooled to a temperature of 320^{o}C, with intercooler effectiveness of 30%, and intercooler pressure loss of 3% of LPC delivery pressure. However, a mass bleed totaling 27% of intake air mass flow is channeled for both HPT and IPT inlet blades cooling. The intercooled engine arrangement is shown in Figure 4-10 in TURBOMATCH bricks, and the DP performance results are summarized in Table 4-4.

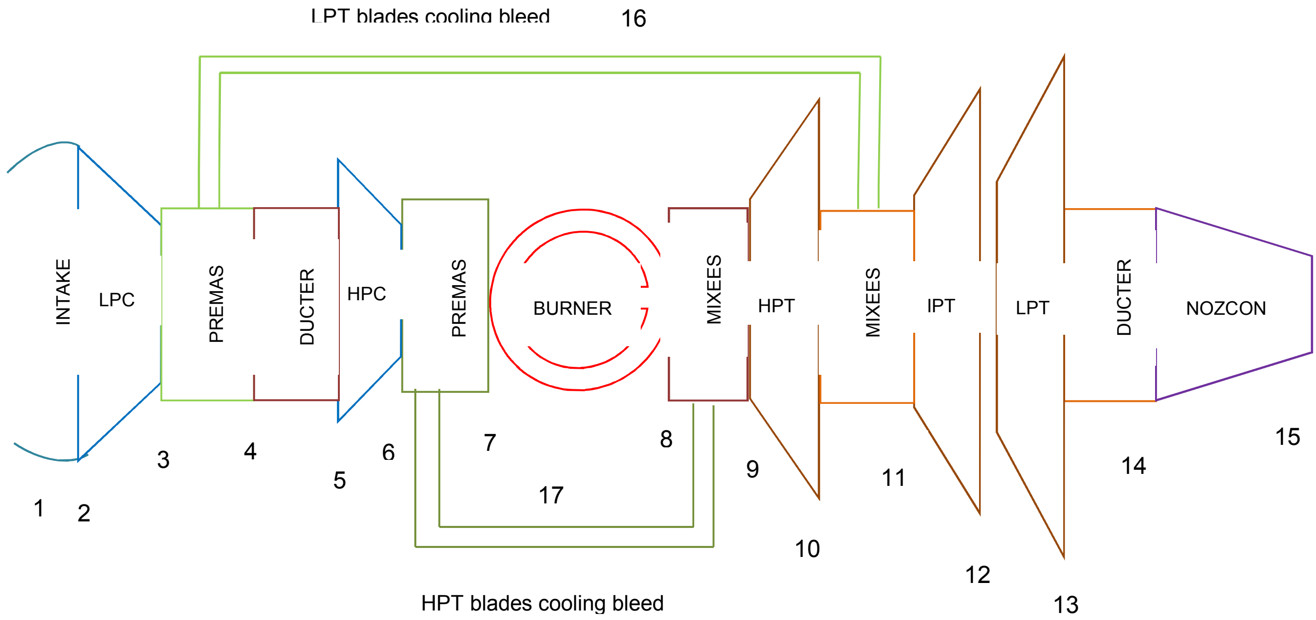

Figure 4-10 Intercooled 3-spool LS2-ADIGT engine components in TURBOMATCH bricks (inspired by GE LMS100 core)

4.3.3.2.3 DP performance of ICR three-spool LS2-ADIGT engine

The intercooled/recuperated three-spool large-scale aero-derivative engine components in TURBOMATCH bricks is shown in

Figure 4-11. The core engine parameters of the intercooled LS-ADIGT described in section 4.3.3.2.2 are retained except for the inclusion of a recuperator of 75% effectiveness, with cold side and hot side pressure losses of 1% and 2% respectively, of the inlet pressure, and 2% mass leakage. The inlet mass flow remains 215.5kg/s with a total of 27.4% bleed for both HPT and IPT inlet blades cooling. Also, keeping ISA SLS as design point, the engine was simulated and the summary of its DP performance shown in Table 4-4. The simulation result file is shown in Appendix B.2 .

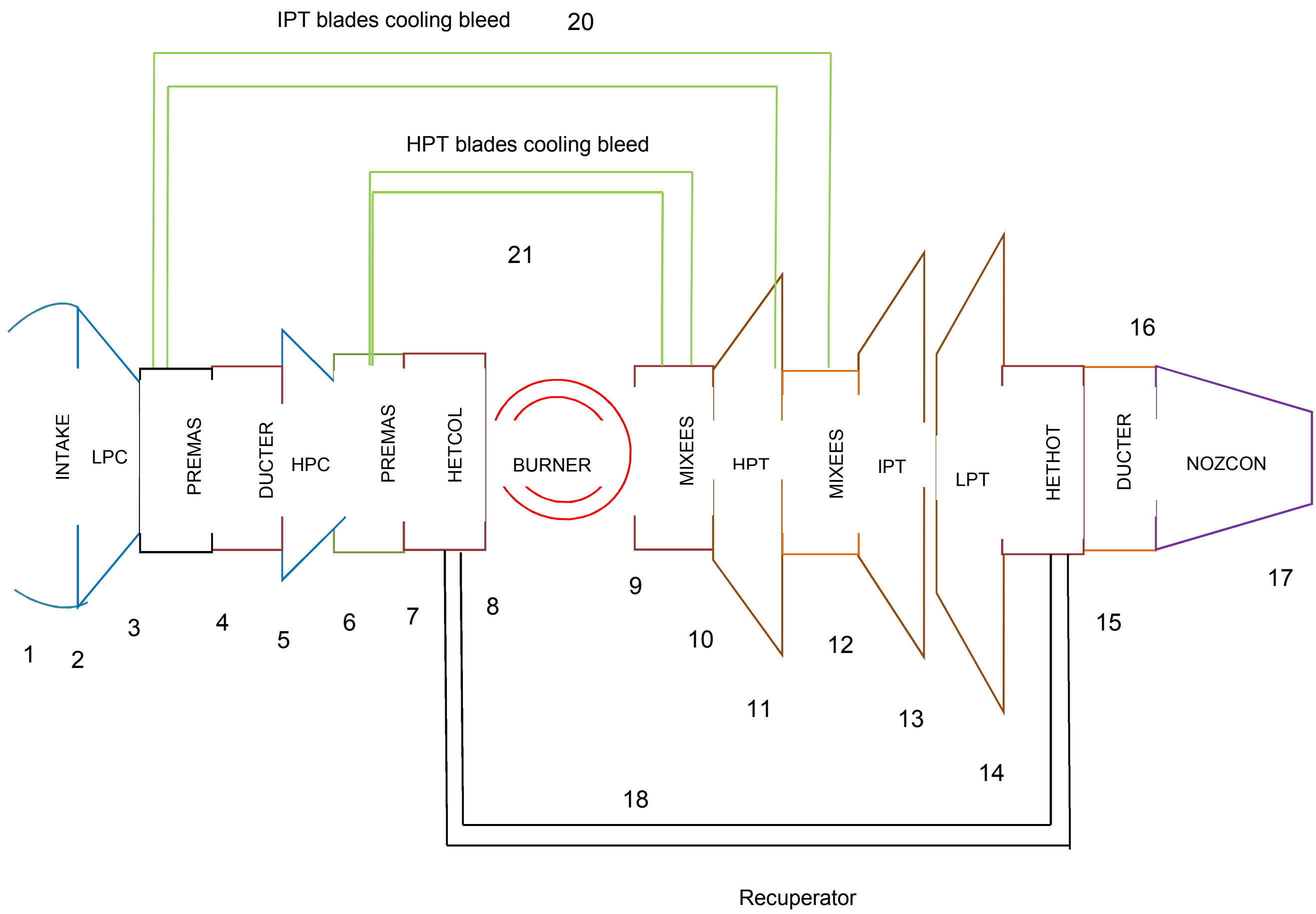

Figure 4-11 Intercooled/recuperated 3-spool LS2-ADIGT engine components in TURBOMATCH bricks (inspired by GE LMS100 core)

Table 4-4 Summary of DP performance results of the LS2-ADIGT engines simulation

Performance parameter	Value at DP of simulated three-spool LS2-ADIGT engines		
	Simple cycle	Intercooled	ICR
Power turbine rating (kW)	100,000	100,000	100,000
Inlet mass flow (kg/s)	215.5	215.5	215.5
Exhaust mass flow (kg/s)	220.59	220.47	220.54
Fuel flow (kg/s)	5.09	4.97	5.04

Performance parameter	Value at DP of simulated three-spool LS2-ADIGT engines		
	Simple cycle	Intercooled	ICR
Exhaust gas temperature (K)	783	692	690
Overall compression pressure ratio	42.15:1	42.15:1	42.15:1
Thermal efficiency	0.457	0.467	0.460

4.3.3.2.4 Verification of performance results of base engine LS-ADIGT

To verify the results of performance parameters of the simulated baseline engine, comparison is made with public domain source reference data of LMS100. This is shown in Table 4-5

Table 4-5 Verifying performance results of simulated LS2-ADIGT engine

Performance parameter	Value at ISA SLS			
	Inspiring core LMS100	Simulated baseline engine	Variation	% variation
Power turbine rating	100,000kW	100,000kW	0.00	0.00
Inlet mass flow	N/A	215.5kg/s	-	-
Exhaust mass flow	220 kg/s	220.47kg/s	-0.47	-0.21
Fuel flow	N/A	4.97kg/s	-	-
Exhaust gas temperature	686K	692K	-6	-0.87
Overall pressure ratio	42.00:1	42.15:1	-0.15	-0.36
Thermal efficiency	0.440	0.467	-0.027	-6.1
TET	N/A	1730K	-	-

4.3.4 Off-design performance results of LS-ADIGT engines

By the use of component maps in TURBOMATCH codes, the off-design performances of the SS-ADIGT engines were simulated and the variation of some key engine output parameters were plotted and presented in Figure 4-12 to Figure 4-16

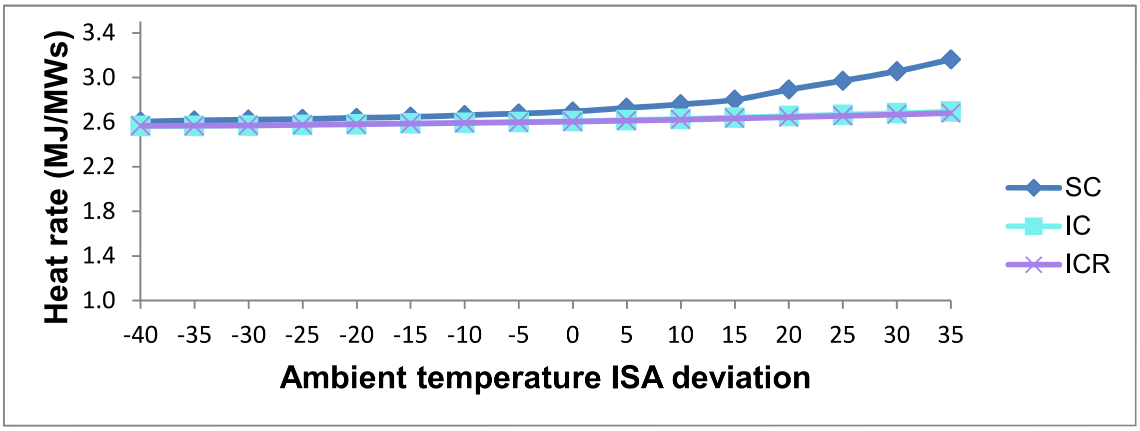

Figure 4-12 Variation of heat rate with ambient temperature (LS1-ADIGT)

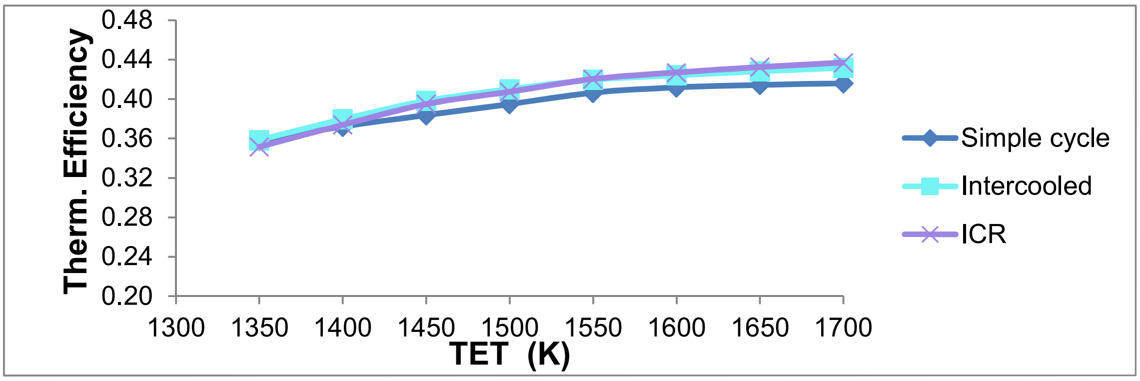

Figure 4-13 Variation of thermal efficiency with TET at ISA SLS (LS1-ADIGT)

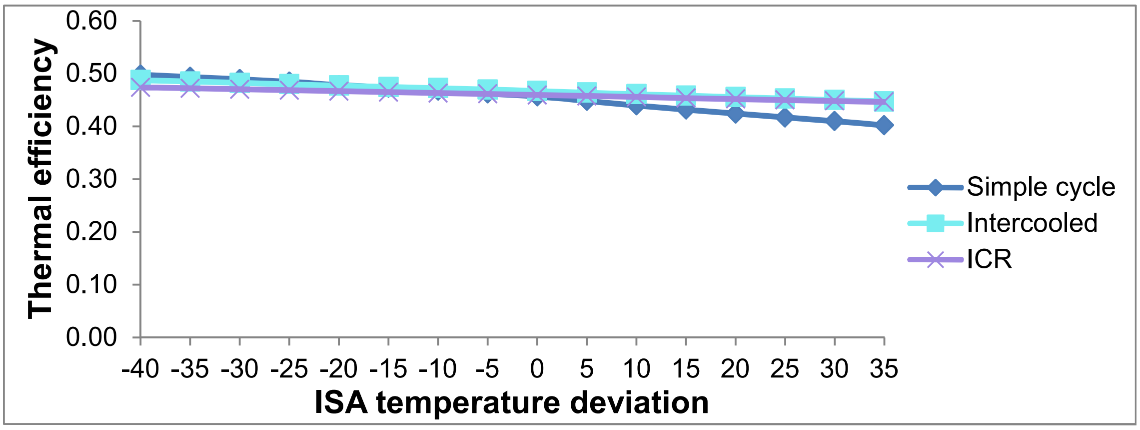

Figure 4-14 Variation of thermal efficiency with ambient temperature at ISA SLS (LS2-ADIGT)

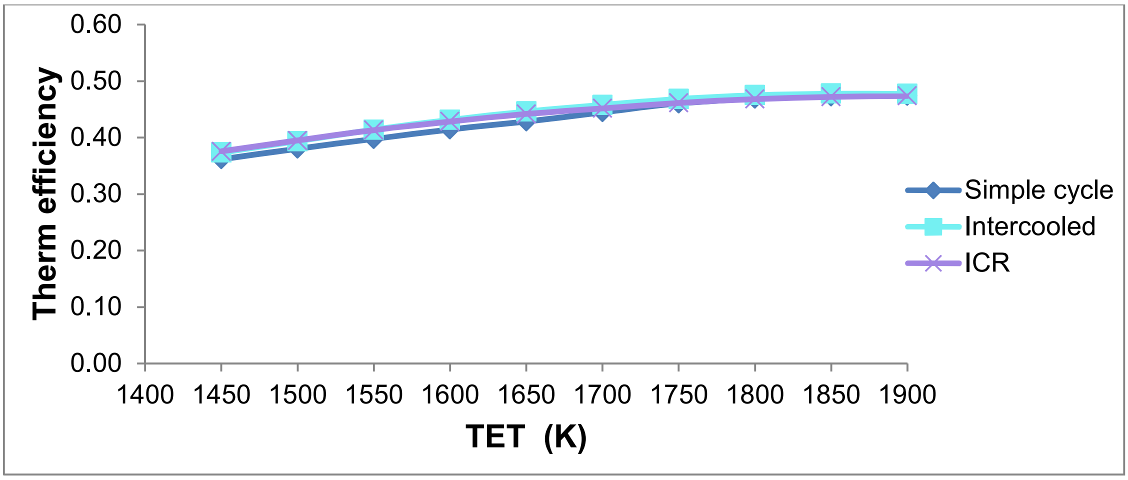

Figure 4-15 Variation of thermal efficiency with TET at ISA SLS (LS2-ADIGT)

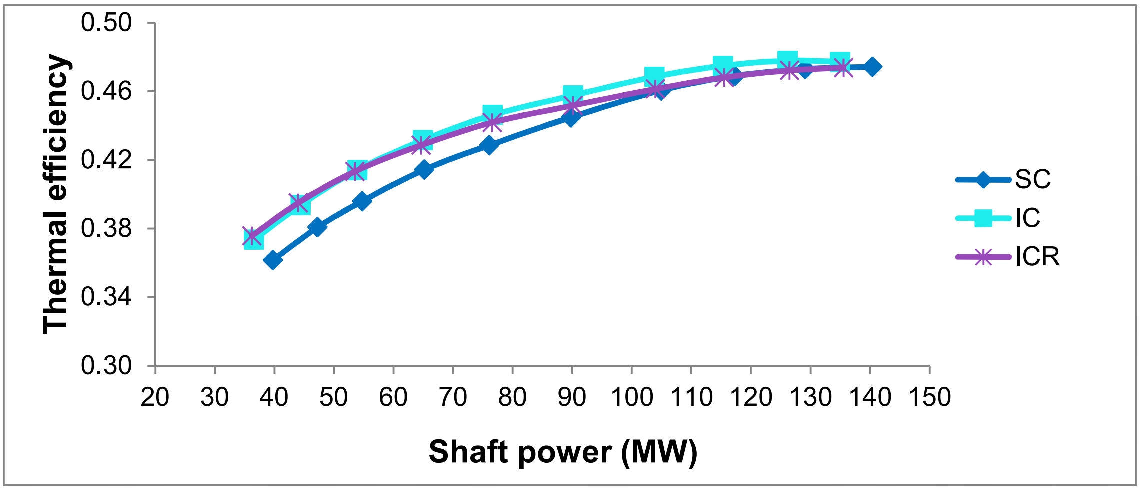

Figure 4-16 Thermal efficiency varying with shaft power at ISA SLS (LS2-ADIGT)

With reference to the simulation results shown in Table 4-2, and Table 4-4, and plots of Figure 4-12 to Figure 4-16, it could be observed that for the LS1-ADIGT and LS2-ADIGT the intercooled, and intercooled/recuperated, engines have increased thermal efficiency, compared to the simple cycle engine at both DP and off-design point. This is due to the fact that the intercooler decreases the temperature of the air entering the HP compressor and as such reduces the HP compressor work. Similarly, recuperator increases the temperature of air entering the combustor to reduce the quantity of heat flow required from burning fuel by heat-exchange action with stream of exhaust gas. The ICR cycle combines both advantages of intercooling and heat-exchange discussed above to achieve increased thermal efficiency. In the same vein, heat rate is reduced in the advanced cycles compared to the simple cycle

In Figure 4-17 to Figure 4-18, the percentage increases at DP in thermal efficiency of the advanced cycle engines over the simple cycle engine are shown.

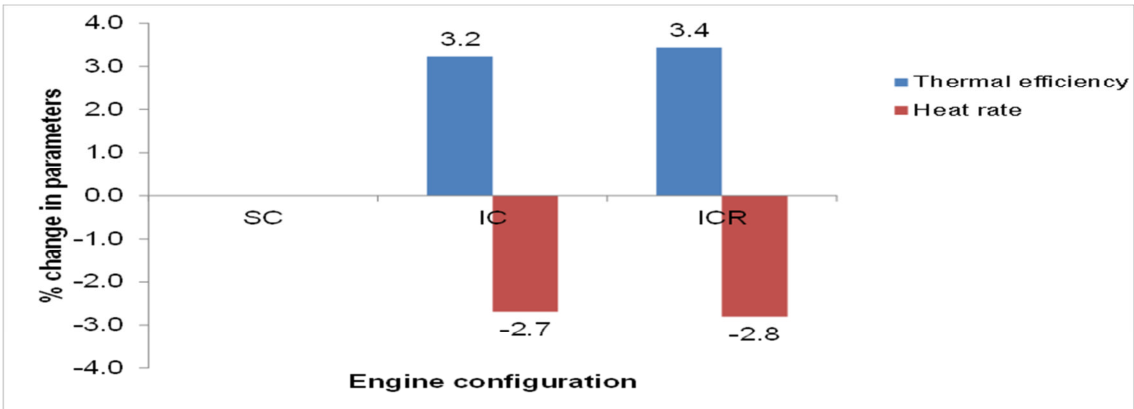

Figure 4-17 Percentage change in performance parameters of IC and ICR cycles over simple cycle for the LS1-ADIGT

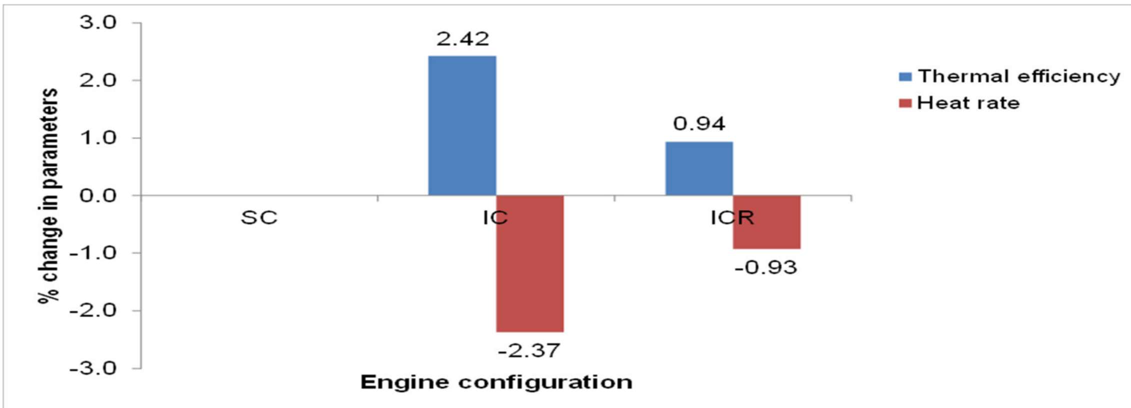

Figure 4-18 Percentage change in performance parameters of IC and ICR cycles over simple cycle for the LS2-ADIGT engines

The negative sign on the heat rates in the figures above indicate percentage reduction in heat rate of advanced cycles over simple cycle. Of-course increase in thermal efficiency is accompanied with corresponding decrease in heat rate for the ADIGT engines.

However, it is important to note that though the thermal efficiency is improved by using the advanced cycles, the incorporation of intercoolers and recuperators would make the engine more complex. This would increase the capital and maintenance cost actually, but cost of fuel would reduce due to reduction in heat rate and fuel consumption.

These results compare favourably with values obtained in the literature. For instance, it was reported that the 1.4MW intercooled/recuperated Heron-1 turbo-shaft gas turbine manufactured by EECT of the Netherland, exhibits thermal efficiency of 42.9% while a simple cycle gas turbine of same power range has thermal efficiency of about 26 - 34%. This represents a thermal efficiency increase of about 26.2% at the minimum (Farmer, 2002). More so, percentage increases were reported of thermal efficiencies of recuperated engine cycle, and intercooled/recuperated engine cycle, over simple cycle of a turbo-shaft engine at DP as 20.6%, and 24.2% respectively, whereas percentage reduction in specific fuel consumption of these cycles over simple cycle at DP as 17.3%, and 21.1% respectively (Nkoi et al, 2013a; Nkoi et al, 2013b).

4.4 Emissions estimation of ADIGT engines

HEPHAESTUS code (discussed in section 2.9.3) is employed to estimate engine emissions by simulation for all the ADIGT engines. Assuming a conventional combustor using natural gas as fuel, parameters at the combustor inlet are made inputs to the model. Such parameters include air inlet total temperature, air inlet total pressure, fuel mass flow, and total air mass flow. Others are ambient temperature, and ambient relative humidity. The code incorporates DLN technology whereby bled excess air mass flow is utilised to reduce combustor flame temperature. In all ADIGT categories, compliance to low NO_x emission target limit of 25ppm (2.0 g/kg fuel) is kept.

4.4.1 Emissions estimation of SS-ADIGT engines

In simulating the DP emissions of the SS-ADIGT engines the International Civil Aviation Organisation (ICAO) target of 25ppm (2.0 g/kg fuel) of NO_x was matched in HEPHAESTUS as this model was derived in this project and there are no information on its emission level in the literature. The DP emission indices (EI) results are presented in Table 4-6.

Table 4-6 Design point emissions indices for the SS-ADIGT engine cycles

Engine cycle	$EINO_X$ (g/kg fuel)	EICO (g/kg fuel)	$EICO_2$ (g/kg fuel)	EIH_2O (g/kg fuel)
SC (base engine)	2.00	0.16	2856.11	2223.56
RC	1.93	0.13	2859.99	2223.98
ICR	1.90	0.16	2856.61	2223.61

The off-design emissions performances of the SS-ADIGT engines are shown in the plots of Figure 4-19 and Figure 4-20

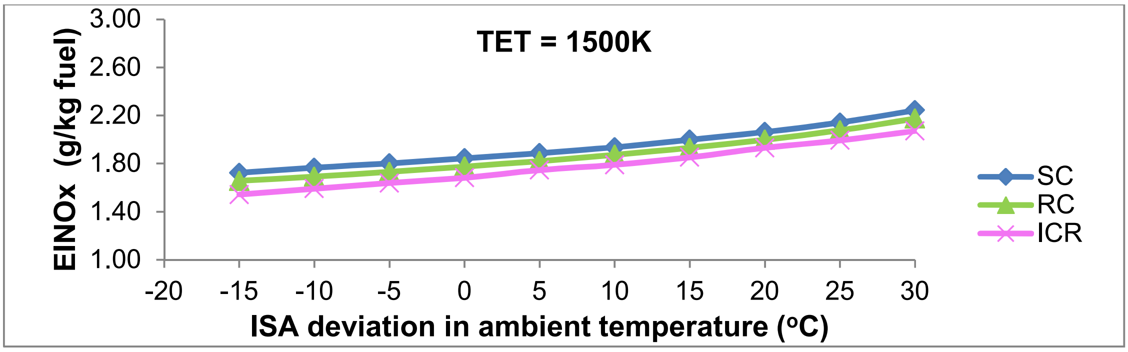

Figure 4-19 Variation of No$_x$ emisson index with amb. temperature (SS-ADIGT)

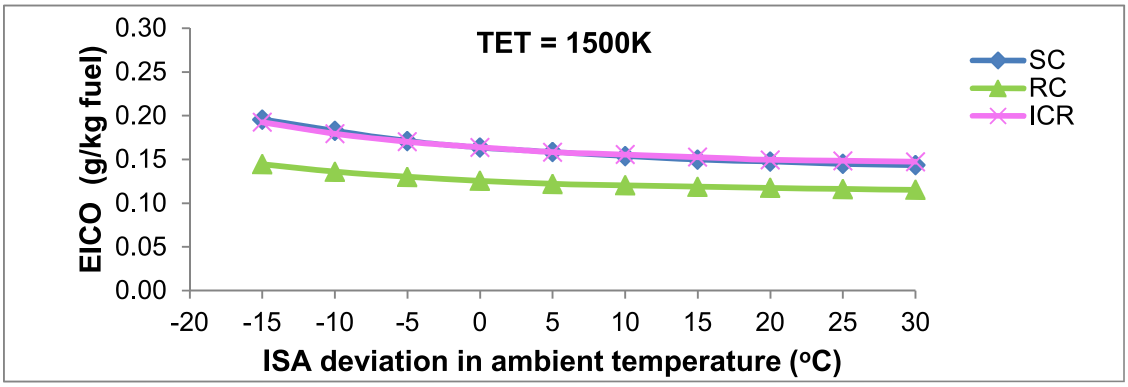

Figure 4-20 Variation of CO emisson index with amb. temperature (SS-ADIGT)

4.4.2 Emissions estimation of LS1-ADIGT engines

Matching the EINO$_x$ of the base LS1-ADIGT engine at DP with the specified 1.20g/kg fuel (15ppm) EINO$_x$ of the engine inspired by LM6000 PD core, the emissions performances were simulated and DP results are presented in Table 4-7.

Table 4-7 Design point emissions index for the LS1-ADIGT engine cycles

Engine cycle	EINO$_x$ (g/kg fuel)	EICO (g/kg fuel)	EICO$_2$ (g/kg fuel)	EIH$_2$O (g/kg fuel)
SC (base engine)	1.20	0.15	2858.61	2223.79
IC	1.17	0.22	2854.33	2223.27
ICR	1.11	0.21	2854.67	2223.29
inspiring engine core - LM6000-PD	1.20 (15ppm)	N/A	N/A	N/A

The off-design emissions performances of the LS1-ADIGT engines are shown in the plots of Figure 4-21 and Figure 4-22

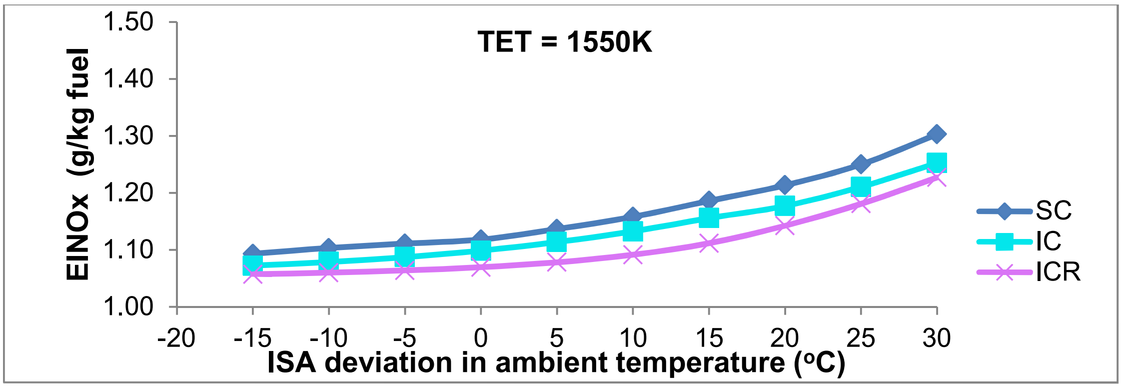

Figure 4-21 Variation of No_x emission with ambient temperature (LS1-ADIGT)

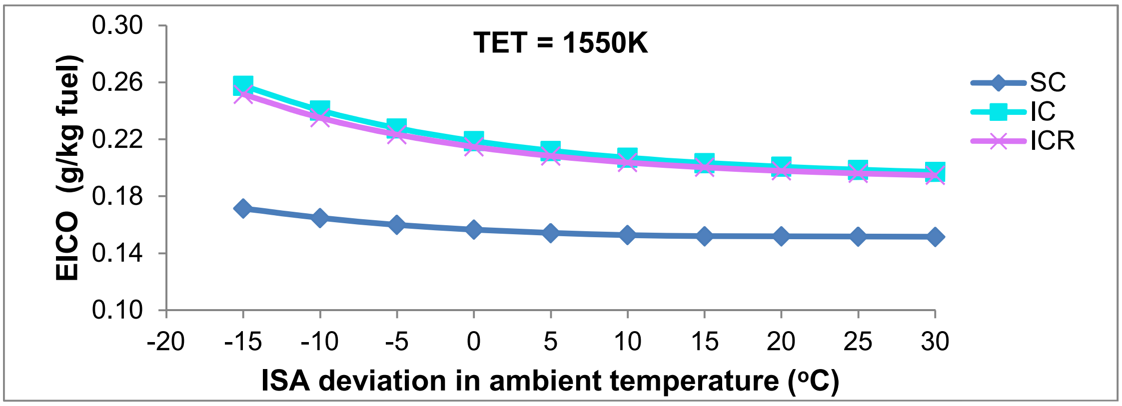

Figure 4-22 CO emission index versus ambient temperature (LS1-ADIGT)

4.4.3 Emissions estimation of LS2-ADIGT engines

The $EINO_x$ of the base-line LS2-ADIGT engine at DP is matched with the specified 2.0g/kg fuel (25ppm) $EINO_x$ of the engine inspired by LMS100 core. The emissions performances were simulated and DP results are shown in Table 4-8

Table 4-8 Design point emissions index for the LS2-ADIGT engine cycles

Engine cycle	$EINO_X$ (g/kg fuel)	EICO (g/kg fuel)	$EICO_2$ (g/kg fuel)	EIH_2O (g/kg fuel)
SC	1.97	0.96	2855.11	2220.99
IC (base engine)	1.94	1.32	2851.07	2220.45
ICR	1.92	1.37	2850.68	2220.39
inspiring engine core - LMS100	2.00 (25ppm)	N/A	N/A	N/A

The off-design emissions performances of the LS2-ADIGT engines were simulated and results are shown in the plots of Figure 4-23 and Figure 4-24

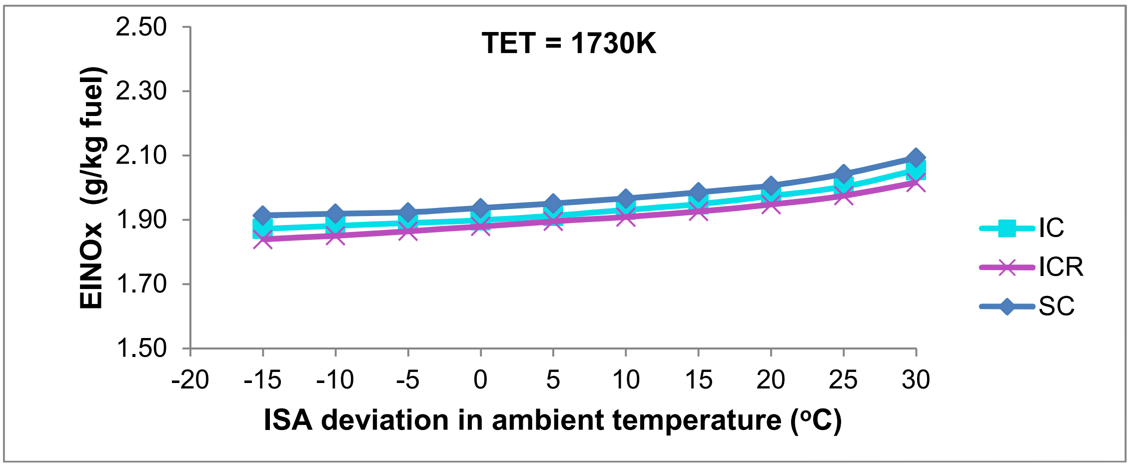

Figure 4-23 Variation of No_x emission with ambient temperature (LS2-ADIGT)

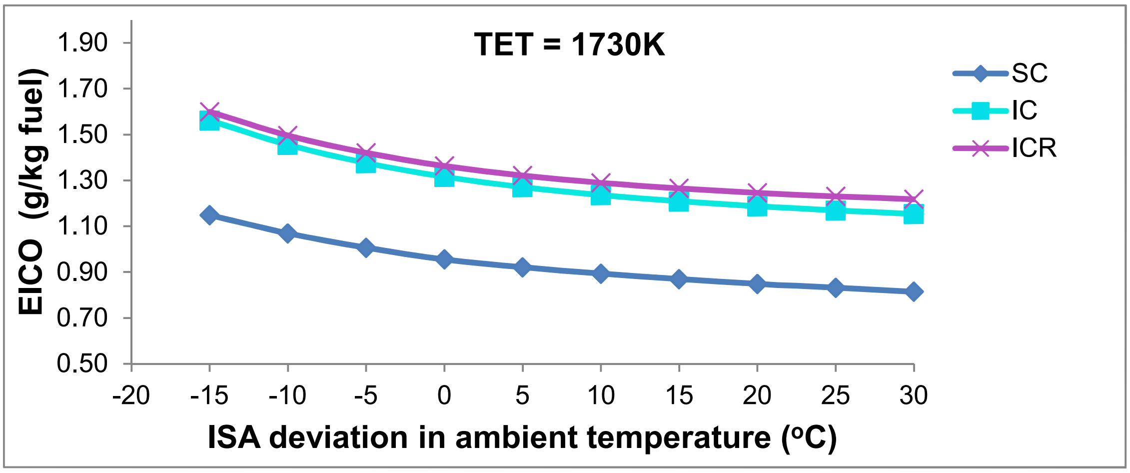

Figure 4-24 CO emission versus ambient Temperature (LS2-ADIGT)

It is worth mentioning that the emissions that constitute toxic pollutants to the environment are No_x and CO. As shown in Figure 4-19 to Figure 4-24 it is rightfully observed that as NOx emission increases with ambient temperature rise, CO emission decreases. This is true because increase in ambient temperature depicts some percentage increase in combustion flame temperature which favours production of NOx and retards production of CO. Thus, in the emission simulation models compromise for CO emission was reached in attempting to reduce NO_x emission by DLN application. This explains why engine cycles with low NOx emission tend to exhibit high CO emission and vice versa.

4.5 Chapter summary

In this chapter the following are described:

- Conversion of helicopter gas turbines to SS-ADIGT is done.
- Performance analysis of simple, RC and ICR cycles SS-ADIGT derived from helicopter gas turbines is implemented.
- Performance analysis of simple, IC and ICR cycles LS1-ADIGT inspired by GE LM6000 core is carried out.
- Performance analysis of simple, IC and ICR cycles LS2-ADIGT inspired by GE LMS100 core is done.
- Verification of base engines are done by comparing simulated performance parameters with values of the inspiring GE LM6000 and GE LMS100 cores obtained in the literatures.
- Estimation of NO_x, CO, CO_2, H_2O emissions indices of SS-ADIGT is done.
- Estimation of NO_x, CO, CO_2, H_2O emissions indices of LS1-ADIGT is achieved.
- Estimation of NO_x, CO, CO_2, H_2O emissions indices of LS2-ADIGT is implemented.
- It is found that for the SS-ADIGT the RC and ICR cycles exhibit better thermal efficiency than the simple engine.
- For both the LS1-ADIGT and LS2-ADIGT the IC and ICR cycles show increased thermal efficiency than the simple engine.
- Similarly, in all categories of ADIGT engines, heat rate in combustor is reduced in the advanced cycles than the simple engine.
- It is observed that NO_x emission increases with increasing ambient temperature while CO emission decreases with same.
- It is observed that engine cycles with low NOx emission tend to exhibit high CO emission.

5 METHODOLOGY AND ANALYSIS OF ADIGT COMBINED-HEAT-AND-POWER (CHP) IN THE PETROCHEMICAL INDUSTRY

5.1 Overview

In contemplating environmentally-friendly Brayton cycles in the petrochemical industry identification is made of CHP as one prominent application that would make gas turbine operation very pleasant to the environment in the aspects of reducing heat energy loss to the environment, and reducing global warming. It also enhances fuel efficiency. CHP simply defined is the simultaneous generation of mechanical power and heat energy in a single system from same fuel input (International Energy Agency, 2007). The benefit of CHP is illustrated in Figure 5-1 where a CHP plant with a single 100 units fuel source yields 75% overall cycle efficiency as against separate power plant and boiler sources of an aggregate of 147 units of fuel yielding 51% overall cycle efficiency. In light of this, the performance of the categories of ADIGT discussed in the last chapter is herein analysed in CHP application in the petrochemical industry.

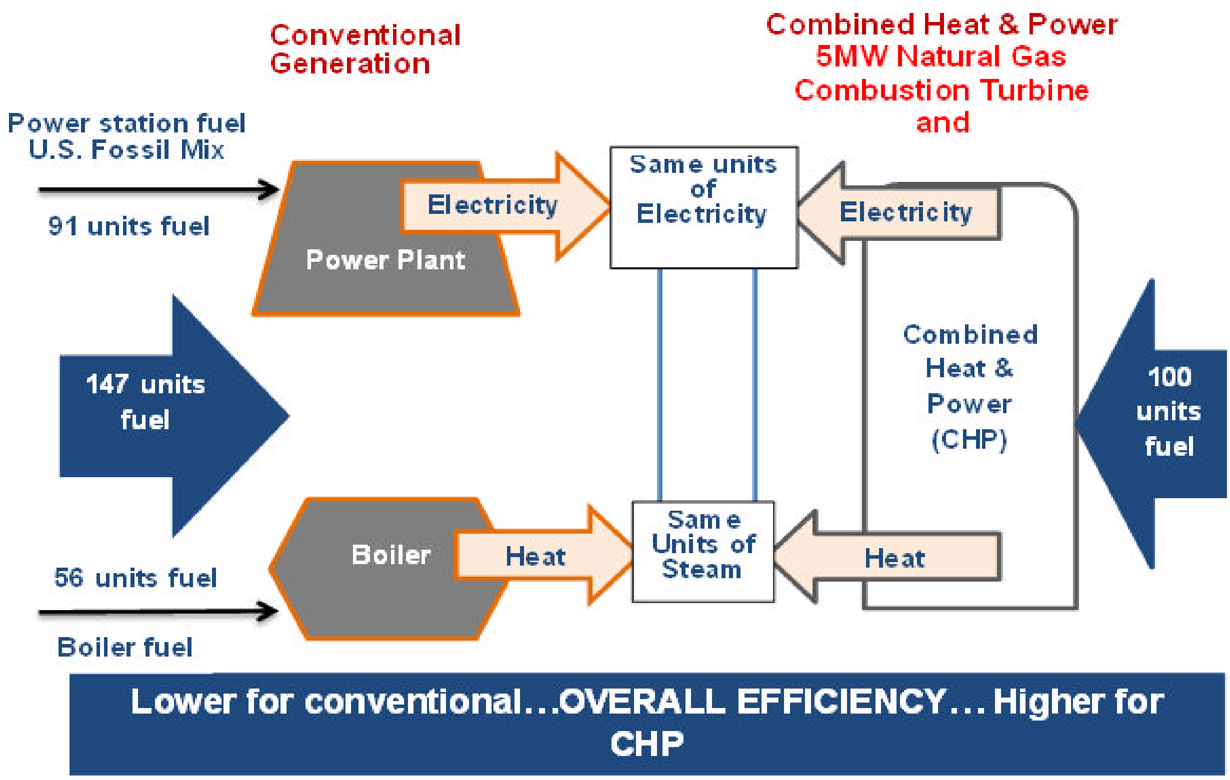

Figure 5-1 Energy saving benefit of CHP over traditional system

(Source: U.S EPA, 2013)

Firstly, a review of petrochemical and refinery processes that utilise steam (heat energy) is presented. Then the methodology adopted for CHP analysis is described. This is followed by modelling of CHP performance of the simple and advanced cycles SS-, LS1-, and LS2-ADIGT engines.

5.2 Petrochemical industry processes

In the context of this research petrochemical industry would encompass both refineries and petrochemical processing plants where crude oil and natural gas are transformed into various hydrocarbon compounds and finished products. It is important to declare that these industry processes are not treated here in detail but rather focus is only made of the process heat energy and power demands of the plants.

5.2.1 Refinery processes

Petroleum refining is the mother industry for petrochemical industries (Verma, 2011). Crude oil is refined and transformed into various products by three major processes: separation, conversion, and purification (Exxonmobil, 2011). The process of distillation in columns by virtue of boiling point differences is used to separate the various primary components of the crude by vaporising it through the action of heat supplied by a furnace. Such fractions as gases, naphtha, jet oil, gas oil, heavy gas oil, and atmospheric residue, are tapped at various sections along the column. The distillation column temperature ranges from about 370^{o}C at the bottom to about 30^{o}C at the top. Conversion process is utilised to transform low-grade fuel oil into high-grade gasoline, and other lighter products. Catalytic cracking unit is employed to convert heavier hydrocarbons into petrol, liquefied petroleum gas, and diesel under the action of heat. Reforming is another conversion process used to increase petrol blends octane number, and to produce hydrogen that would further be used in the refinery. Finally, in order to meet specifications of product quality and environmental standard after separation and conversion, the resulting products are purified mainly to remove sulphur (Exxonmobil, 2011).

5.2.2 Petrochemical processes

Many processes occur in the petrochemical industry, but from the perspective of energy consumption, the most important technologies are: steam cracking of heavier feedstock, polymerisation, and processing of aromatics (Gielen et al, 1996). In steam cracking feedstock such as naphtha and gas oil are converted at elevated temperatures into a wide array of products such as olefines (ethylene, propylene, and butylene), aromatics (benzene, toluene, and xylene), pyrolysis gasoline, and methane. Polymerisation is the process whereby small compounds called monomers are linked together to yield chains of larger products called polymers. Polymerisation technology is generally based on catalytic conversion at temperatures above 100°C and at elevated pressures. The four most important polymers (plastics) produced by this means are: polyethylene, polypropylene, polystyrene, and polyvinylchloride.

5.2.3 Steam utilization

Some processes in the petrochemical industry like some of the ones mentioned in the last two sections occur at relatively moderate temperatures (below 600°C), and steam is generally the source of their heat energy supply. Steam could be generated by conventional boilers or heat recovery steam generators in CHP application. It is worth stating that combined-heat-and-power (CHP) generation of steam and power is presently a key energy saving, as well as environmentally-friendly technology in the petrochemical industry (Gielen et al, 1996).

5.3 CHP modelling

CHP systems are either developed as “topping cycles” or “bottoming cycles” as illustrated in Figure 5-2 and Figure 5-3 respectively. Topping cycles describe systems where there occur primary power generation and subsequent heat utilization, whereas bottoming cycles pertain to systems where heat is primarily generated in a process with subsequent utilisation for power generation (Bhatt, 2001). In this work, topping cycle arrangement is adopted where power is primarily generated from gas turbine and heat recovery steam generator (HRSG) is designed to match for the purpose of process steam production. Performance parameters of the aero-derivative gas turbines discussed in the previous chapter are employed to determine the parameters of the HRSG.

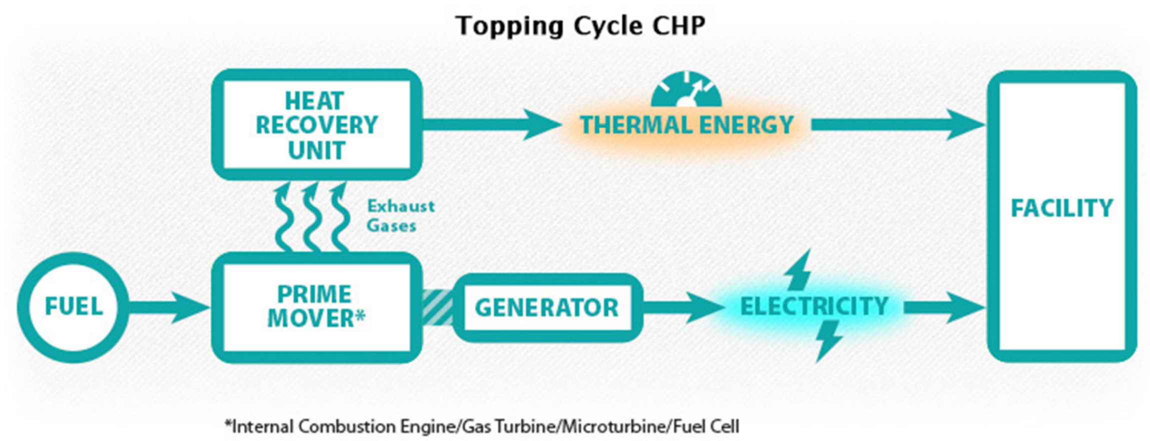

Figure 5-2 Topping cycle CHP (Source: Center for Sustainable Energy, 2014)

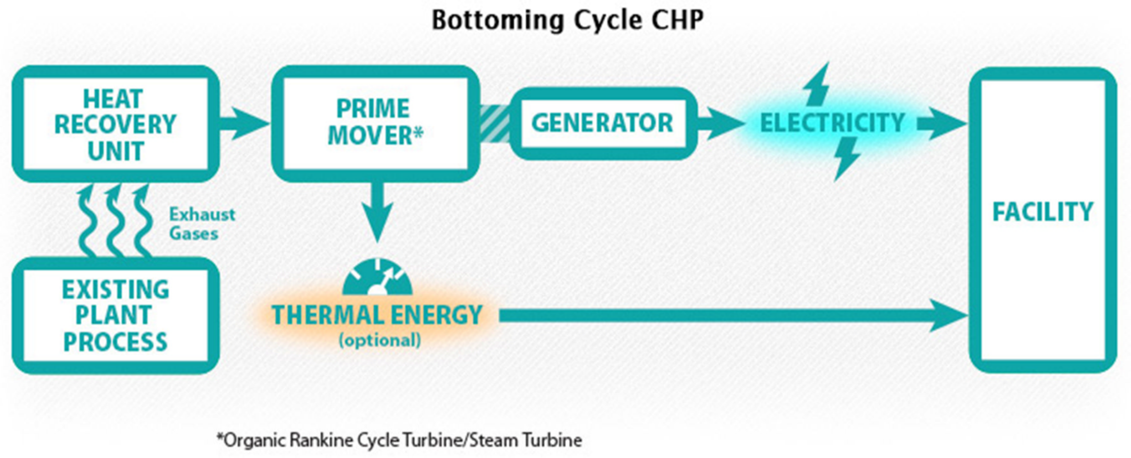

Figure 5-3 Bottoming cycle CHP (Source: Center for Sustainable Energy,2014)

5.3.1 HRSG performance modelling

A set of heat exchangers that utilises the exhaust heat of a gas turbine to produce steam is referred to as heat recovery steam generator (HRSG). Three types of HRSG are identified, namely, unfired, supplementary fired, and exhaust fired. The most common and widely used HRSG is the unfired type because it is simple in design and cheap (Ganapathy, 1996). HRSG of the unfired type is considered in this research without considering the material dimension of the heat exchangers. It is pertinent to declare that only the thermodynamic performance in terms of temperature profile of exhaust gas, steam temperature and flow, and heat capacity, of the HRSG are being modelled in this research.

Pinch and approach point technology is applied in modelling the HRSG performance, and with a single steam pressure mode of operation.

5.3.1.1 Pinch and approach points technology

Approach point is the difference between the temperature of saturated steam and the temperature of water entering the evaporator, whereas pinch point is the difference between the gas temperature leaving the evaporator and the temperature of saturated steam (Ganapathy, 1996). Steam generation is directly affected by the pinch and approach points. Also affected is the exhaust gas and steam temperature profile. For the design case of an unfired HRSG, selection is usually made of the values of pinch and approach points; pinch point ranges from 10^{o}C to 30^{o}C whereas approach point ranges from 5^{o}C to 15^{o}C based on the sizes of evaporators that can be built and shipped economically, and to maximise heat transfer rate between exhaust gas and steam streams. Figure 5-4 illustrates pinch point, approach point, exhaust gas and steam temperature profiles of HRSG.

5.3.1.2 Advantages and disadvantages of low pinch point

Low pinch point has the advantage of enhancing high rate of heat transfer between gas turbine exhaust gas and water/steam in the HRSG. This enables the generation of more steam (more HRSG duty). If generation of less steam is desired such as in a multiple-pressure HRSG generating more low pressure steam than high pressure steam, then a larger pinch value may be selected.

On the other hand, very low pinch would results in very large surface area of HRSG evaporator, which would mean manufacture of a bigger size evaporator. This in essence would not be economical, and also, shipping may be difficult. More so, very Low approach point may result in steaming in the economiser. Economiser steaming could cause operational problems such as vibration, water hammer, and possibly salt depositions in the economiser tubes. These would ultimately reduce HRSG performance (Ganapathy, 1996).

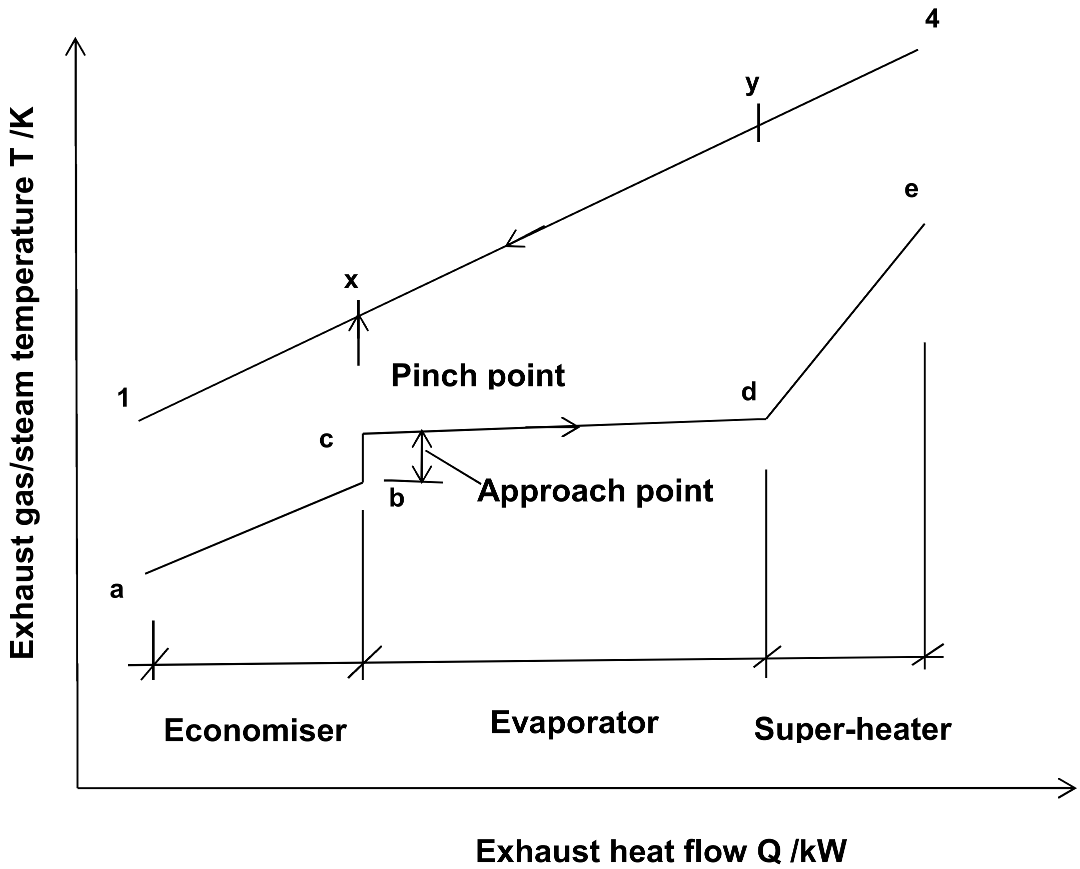

Figure 5-4 HRSG exhaust gas/steam temperature profiles

Using the notations in Figure 5-4 above the path 4-y-x-1 indicates gas turbine exhaust gas temperature profile whereas the path a-b-c-d-e indicates steam temperature profile. Pinch point = $T_x - T_c$; approach point = $T_c - T_b$; process a-b occurs in the economiser; c-d in the evaporator; and d-e in the super-heater.

5.4 ADIGT-CHP design point performance modelling

To model the design point performance of a CHP plant is to match the parameters of HRSG with the design point of the gas turbine given particular consideration to desired steam flow or temperature and saturation pressure. In doing so, pinch and approach points are selected by the engineering judgement; and from gas turbine exhaust gas flow, the HRSG temperature profile, duty, and steam flow are established. Using pinch technology and thermodynamic properties of steam, the computation of CHP HRSG gas/steam temperature profile and steam flow is done as follows:

Gas turbine exhaust gas temperature and mass flow are imported from gas turbine performance simulation while the HRSG pinch and steam saturation pressure (which fixes the steam saturation temperature - T_c) are selected. In this design the steam saturation pressure is 10bar. With the notations of Figure 5-4 the temperature of exhaust gas at pinch point (T_x) is given by Equation 5-1

$T_x = T_c + \text{pinch} = T_c + 15$ **Equation 5-1**

Where pinch = 15

The superheated steam temperature (T_e) is chosen as required by the industrial process heat demand. The steam flow (w_s) is computed from total heat transfer in super-heater and evaporator using **heat balance above pinch** as defined by Equation 5-2

$Q_{4x} = Q_{evap} + Q_{super}$; $Q_{4x} = w_g c_{pa}(0.99)(T_4 - T_x) = w_s[(h_e - h_c) + 0.02(h_d - h_c)]$;

$$\therefore w_s = \frac{w_g c_{pa}(0.99)(T_4 - T_x)}{(h_e - h_c) + 0.02(h_d - h_c)}$$ **Equation 5-2**

Where 0.99 = heat loss factor

0.02 = blow down factor

w_g = exhaust gas flow

c_{pa} = specific heat at constant pressure of air

h_e = specific enthalpy of super-heated steam

h_c = specific enthalpy of saturated water

h_d = specific enthalpy of saturated steam

T_4 = gas turbine exhaust temperature

Q_{evap} = evaporator duty

Q_{super} = super-heater duty

Equation 5-3 defines the super-heater duty (Q_{super})

$Q_{super} = w_s(h_e - h_d)$ **Equation 5-3**

Gas temperature drop in the super-heater (ΔT_{4y}) is given by Equation 5-4

$\Delta T_{4y} = \frac{Q_{super}}{w_g c_{pa}(0.99)}$ **Equation 5-4**

This implies that exhaust gas temperature to evaporator (T_y) is calculated using Equation 5-5

$T_y = T_4 - \Delta T_{4y}$ **Equation 5-5**

Evaporator duty (Q_{evap}) is determined with the aid of Equation 5-6

Evaporator duty $Q_{evap} = w_s(h_d - h_c)$ **Equation 5-6**

Similarly Equation 5-7 defines Economiser duty (Q_{econ})

Economiser duty $Q_{econ} = w_s\,(1.02)(h_c - h_a)$ **Equation 5-7**

Gas temperature drop in the economiser (ΔT_{x1}) is given by Equation 5-8

$\Delta T_{x1} = \frac{Q_{econ}}{w_g c_{pa}(0.99)}$ **Equation 5-8**

This implies that exhaust gas exit temperature from the economiser (T_1) is calculated using Equation 5-9

$T_1 = T_x - \Delta T_{x1}$ **Equation 5-9**

Total HRSG duty (Q_{HRSG}) is computed by Equation 5-10

HRSG duty (Q_{HRSG}) = $Q_{evap} + Q_{super} + Q_{econ}$ **Equation 5-10**

Electrical efficiency = $\frac{P_E}{P_T} = \eta_E$

The electrical efficiency could be assumed, such that
Useful electric power generated $P_E = \eta_E \times P_T$

Where P_T = gas turbine power

Heat to power ratio of the CHP is given by Equation 5-11

Heat to power ratio = Q_{HRSG}/P_E **Equation 5-11**

(Ganapathy, 1990)

Equation 5-12 is used to compute First Law CHP efficiency (η_1)

First Law efficiency $\eta_1 = \frac{\dot{W}_E+\dot{W}_{ST}}{\dot{m}_f \Delta h_f}$ **Equation 5-12**

Where $\dot{W}_E$ = Electrical energy rate

$\dot{W}_{ST}$ = Steam energy rate

$\dot{m}_f$ = fuel mass flow in combustor

Δh_f = LHV = low heating value of fuel

Equation 5-13 is used to compute Second Law CHP efficiency (η_2)

Second Law efficiency $\eta_2 = \frac{\dot{W}_E+\dot{W}_{ST}}{\dot{m}_f\,[\Delta h_f - T_R.\Delta S_f]}$ **Equation 5-13**

The denominator of Equation 5-13 is the availability rate of the fuel consumed.

Where ΔS_f = Entropy released by fuel combustion

T_R = Temperature at exhaust

(Korakianitis, 2012; Korakianitis et al, 2005)

5.4.1 SS-ADIGT-CHP design point performance analysis

The CHP design point computation was done for the SS-ADIGT and the HRSG gas/steam temperature profiles are shown in Figure 5-5 while the CHP DP performance results are indicated in Table 5-1. The detail DP and OD result files for SC, RC, and ICR SS-ADIGT-CHP performances are presented in Appendix C.1 , Appendix C.2 , and Appendix C.3 respectively.

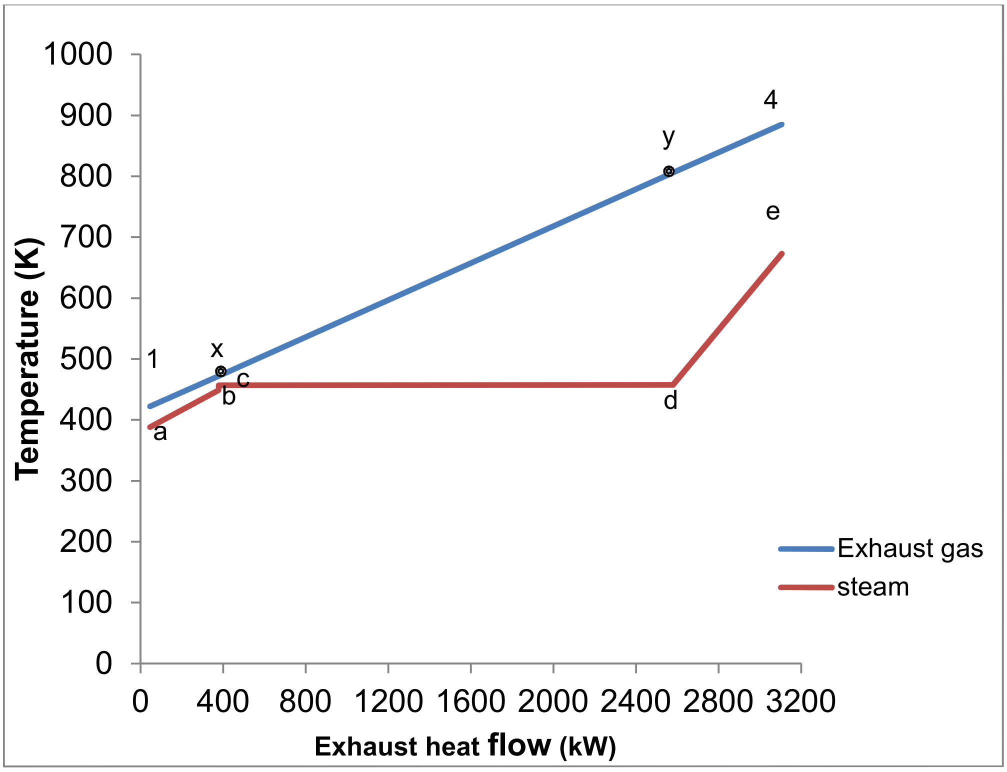

Figure 5-5 HRSG temperature/heat profile for the SS-ADIGT-CHP

Table 5-1 SS-ADIGT-CHP design point performance results

Parameter	Values for the SS-ADIGT engines		
	Simple cycle	Recuperated	ICR
Steam saturation temperature (K)	457	457	457
Pinch point	15	15	15
Approach point	8	8	8
Superheated steam temperature (K)	673	673	673
Steam mass flow (kg/s)	1.10	1.14	0.94
Economiser feed water temperature (K)	388	388	388
Super-heater duty (kW)	530.07	548.80	453.69
Evaporator duty (kW)	2198.23	2275.89	1881.45
Economiser duty (kW)	334.74	346.57	286.50

Parameter	Values for the SS-ADIGT engines		
	Simple cycle	Recuperated	ICR
HRSG duty (kW)	3063.05	3171.26	2621.63
Gas turbine exhaust mass flow (kg/s)	5.65	5.64	5.64
Gas turbine exhaust temperature (K)	885	901	826
Gas temperature at evaporator exit (K)	806	819	758
Gas exit (stack) temperature (K)	422	420	429
Heat : power ratio	2.09	2.16	1.79
CHP efficiency	0.56	0.71	0.60

5.4.2 LS1-ADIGT-CHP design point performance analysis

The CHP design point computation was done for the LS1-ADIGT and the HRSG gas/steam temperature profiles are shown in Figure 5-6 while the CHP DP performance results are indicated in Table 5-2. The detail DP and OD result files for SC, IC, and ICR LS1-ADIGT-CHP performances are presented in Appendix C.4 , Appendix C.5 , and Appendix C.6 respectively.

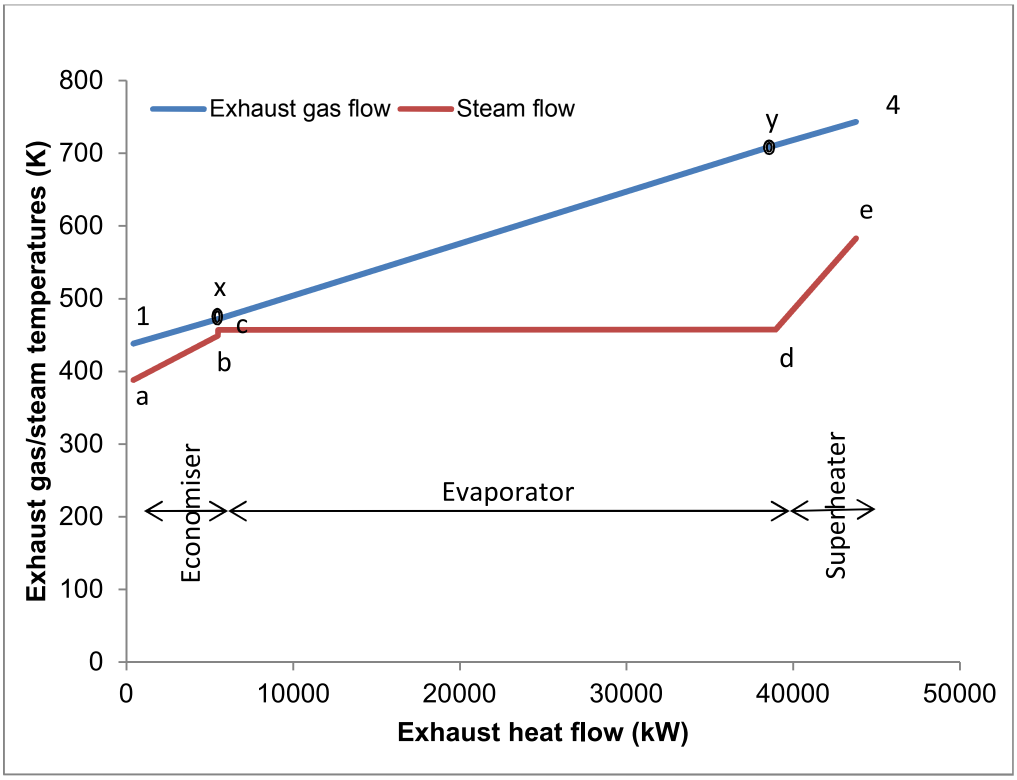

Figure 5-6 HRSG temperature/heat profile for the LS1-ADIGT-CHP

Table 5-2 LS1-ADIGT-CHP design point performance results

Parameter	Values for the LS1-ADIGT engines		
	Simple cycle	intercooled	ICR
Steam saturation temperature (K)	457	457	457
Pinch point	15	15	15
Approach point	8	8	8
Superheated steam temperature (K)	583	583	583
Steam mass flow (kg/s)	17.60	12.03	12.55
Economiser feed water temperature (K)	388	388	388
Super-heater duty (kW)	5094.96	3483.54	3634.73
Evaporator duty (kW)	35180.03	24053.38	25097.35

Parameter	Values for the LS1-ADIGT engines		
	Simple cycle	intercooled	ICR
Economiser duty (kW)	5357.12	3662.78	3821.75
HRSG duty (kW)	45632.10	31199.70	32553.83
Gas turbine exhaust mass flow (kg/s)	127.49	127.42	127.42
Gas turbine exhaust temperature (K)	743	657	665
Gas temperature at evaporator exit (K)	709	634	641
Gas exit (stack) temperature (K)	437	448	447
Heat : power ratio	1.11	0.76	0.79
CHP efficiency	0.65	0.50	0.51

5.4.3 LS2-ADIGT-CHP design point performance analysis

The CHP design point computation was done for the LS2-ADIGT and the HRSG gas/steam temperature profiles are shown in Figure 5-7 while the CHP DP performance results are indicated in Table 5-3. The detail DP and OD result files for SC, IC, and ICR LS2-ADIGT-CHP performances are presented in Appendix C.7 , Appendix C.8 , and Appendix C.9 respectively.

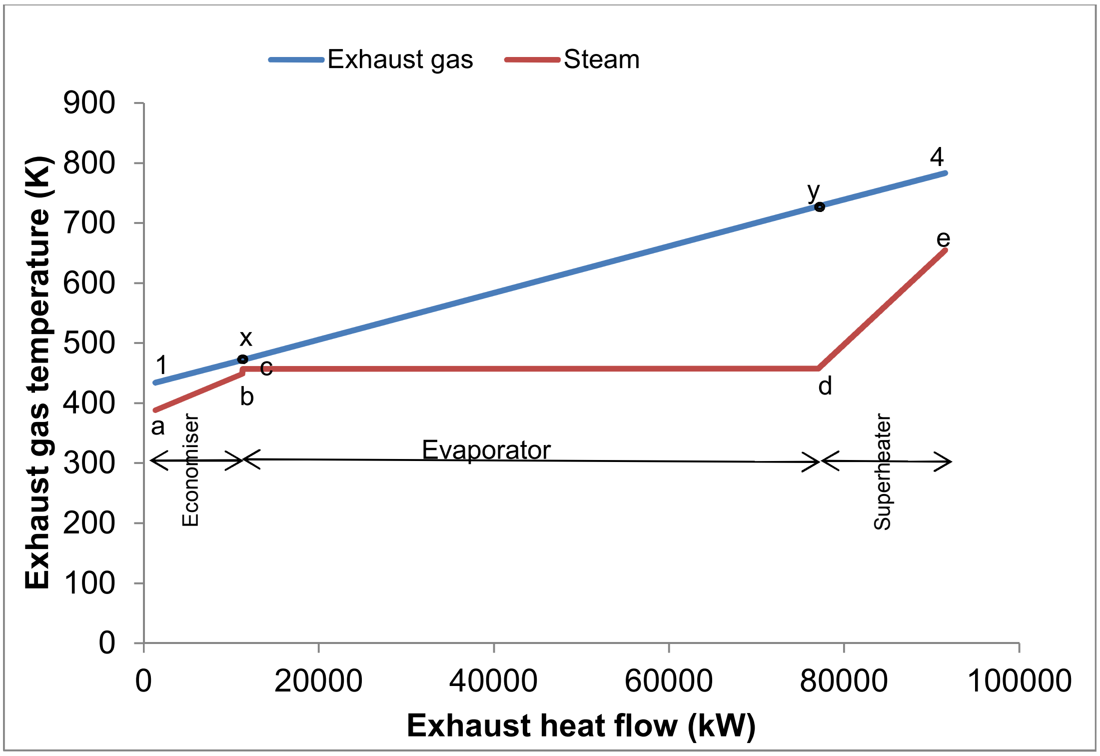

Figure 5-7 HRSG temperature/heat profile for the LS2-ADIGT-CHP

Table 5-3 LS2-ADIGT-CHP design point performance results

Parameter	Values for the LS2-ADIGT engines		
	Simple cycle	intercooled	ICR
Steam saturation temperature (K)	457	457	457
Pinch point	15	15	15
Approach point	8	8	8
Superheated steam temperature (K)	655	655	655
Steam mass flow (kg/s)	32.85	23.16	24.52
Economiser feed water temperature (K)	388	388	388
Super-heater duty (kW)	14572.52	10274.90	10876.51
Evaporator duty (kW)	65664.55	46299.24	49010.14

Parameter	Values for the LS2-ADIGT engines		
	Simple cycle	intercooled	ICR
Economiser duty (kW)	9999.21	705032	7463.13
HRSG duty (kW)	90236.28	63624.45	67349.78
Gas turbine exhaust mass flow (kg/s)	220.59	220.47	220.54
Gas turbine exhaust temperature (K)	783	692	704
Gas temperature at evaporator exit (K)	727	653	662
Gas exit (stack) temperature (K)	434	445	444
Heat : power ratio	0.96	0.68	0.72
CHP efficiency	0.67	0.51	0.52

5.5 ADIGT-CHP off-design performance

The HRSG would normally not operate at the design point due to variations in the inlet gas conditions and steam parameters. The inlet gas conditions in turn would depend on gas turbine off-design variation in ambient conditions, firing temperature, altitude, power setting, etc. This makes the CHP plant exhibits varying outputs. The CHP off-design performance was modelled with TURBOMATCH engine off-design.

The off-design performance results of the CHP of the small-scale and large-scale aero-derivative engines are presented in sections 5.5.1 and 5.5.2 below.

5.5.1 Small-scale-ADIGT-CHP off-design performance results

The off-design performances of the SS-ADIGT-CHP with changing conditions of the engines are shown in Figure 5-8 to Figure 5-12 .

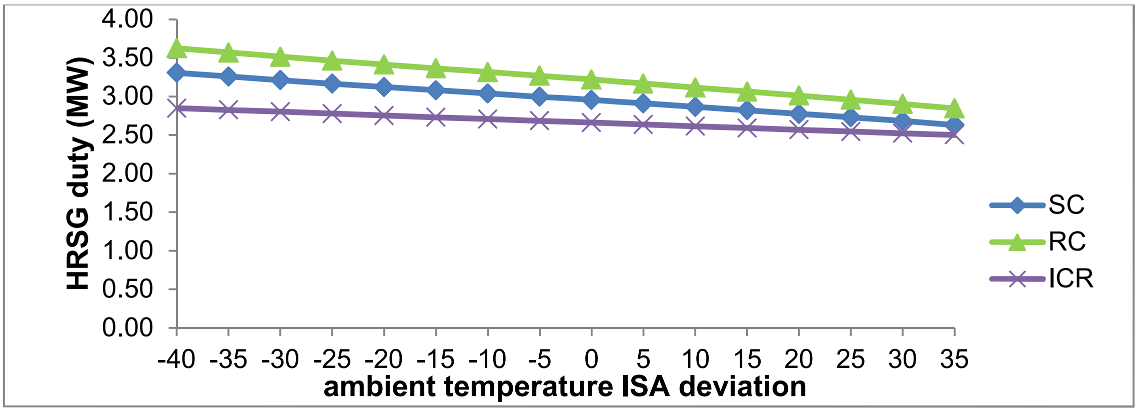

Figure 5-8 Effect of ambient temperature on HRSG duty for the SS-ADIGT-CHP

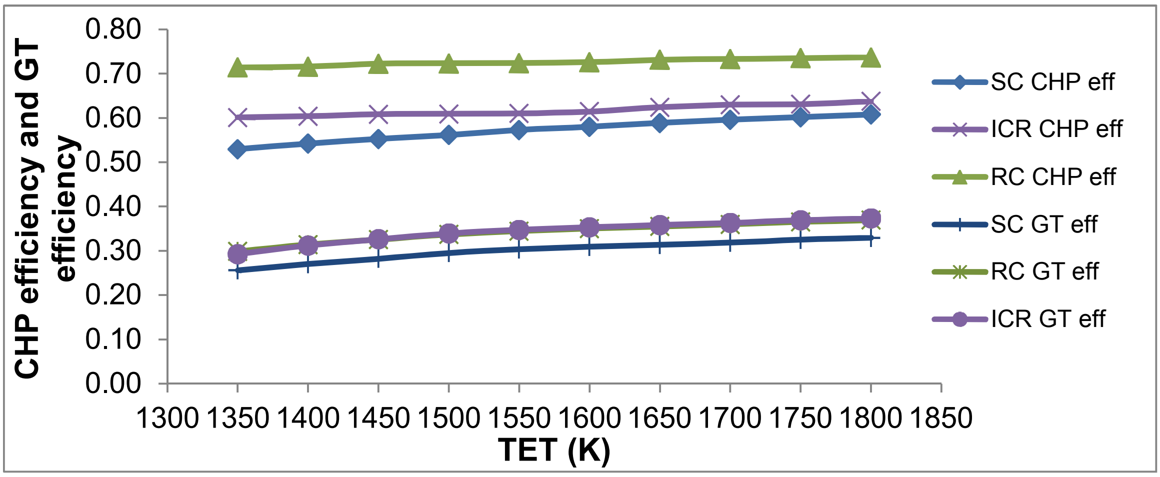

Figure 5-9 Variation of CHP and GT efficiencies with TET for the SS-ADIGT-CHP

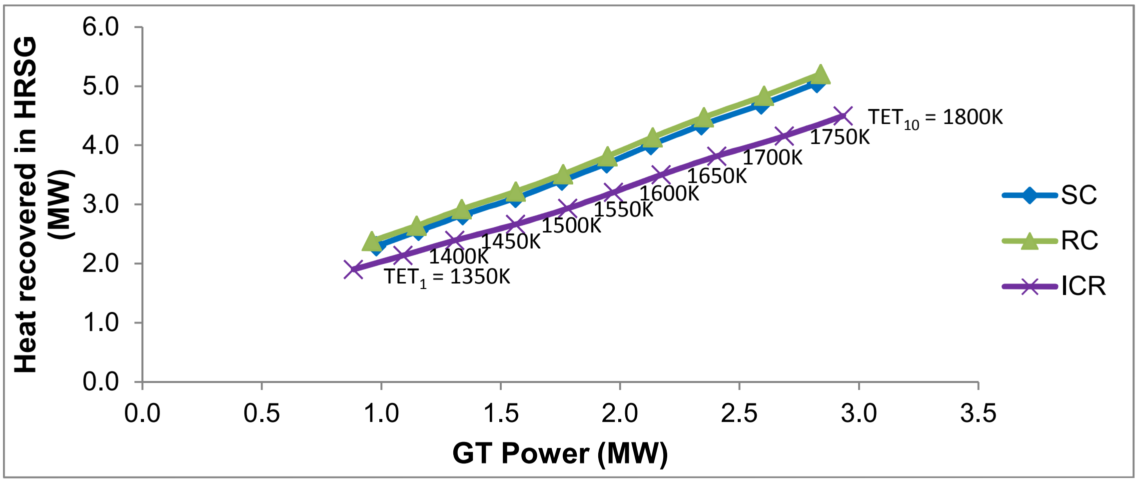

Figure 5-10 Variation of HRSG duty with GT power at increasing TET (SS-ADIGT-CHP)

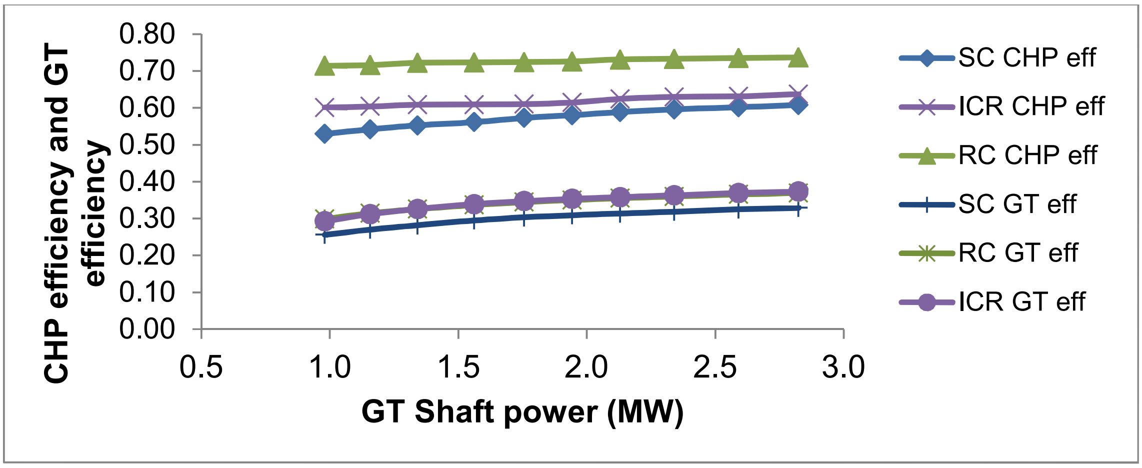

Figure 5-11 Variation of CHP and GT efficiencies with GT power at increasing TET (SS-ADIGT-CHP)

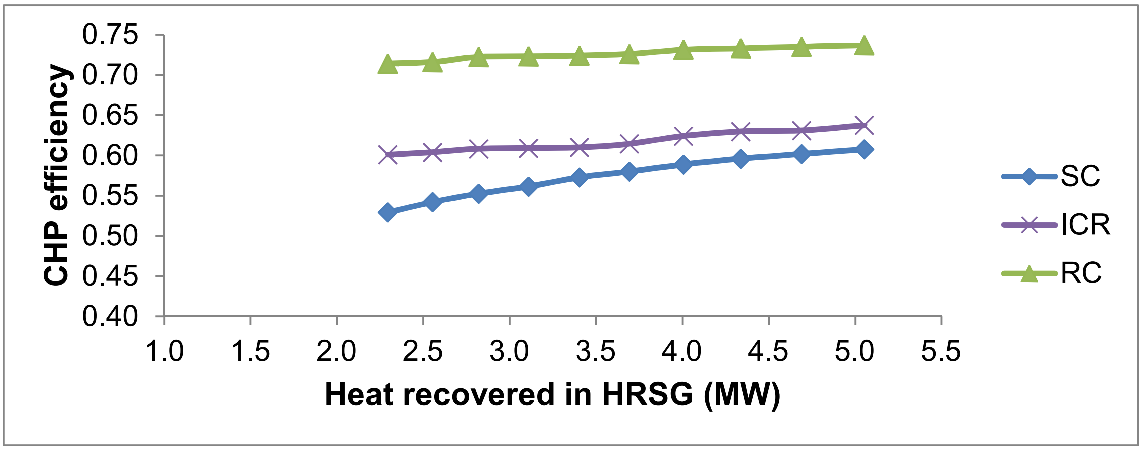

Figure 5-12 Variation of CHP efficiency with HRSG duty at increasing TET (SS-ADIGT-CHP)

At design and off-design conditions the RC and ICR ADIGT engines exhibit better CHP efficiency than the SC engine in the small-scale category as shown in Figure 5-9, Figure 5-11, and Figure 5-12. The CHP efficiencies are observed to increase with increases in TET, GT power, ambient temperature, and HRSG duty. The percentage increases in CHP efficiencies of RC and ICR over SC at DP are 16.5% and 3.8% respectively. This superior performance is due to the lower heat input from burning less fuel in the advanced cycle engines. On the other hand, the SC engine produces more HRSG duty than the ICR cycle as shown in Figure 5-8 and Figure 5-10, due to lower exhaust gas temperature and steam rate of the ICR cycle. The highest HRSG duty is produced by the RC engine because of its higher exhaust gas temperature and steam rate.

Besides, as plotted in Figure 5-10, the heat-to-power ratio is observed to be least in the ICR cycle than SC and RC and highest in the RC cycle at both DP and OD conditions. In essence, this means that given a range of power output at any condition of TET and ambience, the RC cycle would generate more steam than the SC and ICR, while ICR would generate the least steam flow. This is so because GT exhaust gas temperature is highest in the RC cycle and exits the HRSG at the least temperature in the RC cycle. This creates huge drop in temperature of exhaust gas from exit of GT to exit of HRSG in the RC cycle. This exhaust gas temperature drop is smaller in SC cycle and least in ICR cycle. Hence, huge amount of heat is extracted from exhaust gas in RC cycle than SC and ICR at same conditions.

5.5.2 Large-scale-ADIGT-CHP off-design performance results

The off-design performances of the LS1-ADIGT-CHP and LS2-ADIGT-CHP with changing conditions are similar and are presented in Figure 5-13 to Figure 5-19.

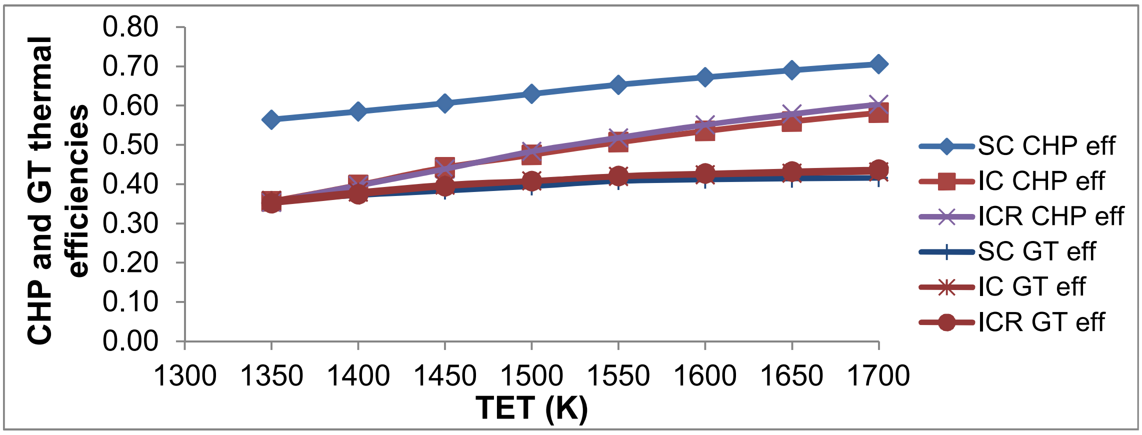

Figure 5-13 Effect of TET on CHP and GT efficiencies for the LS1-ADIGT-CHP

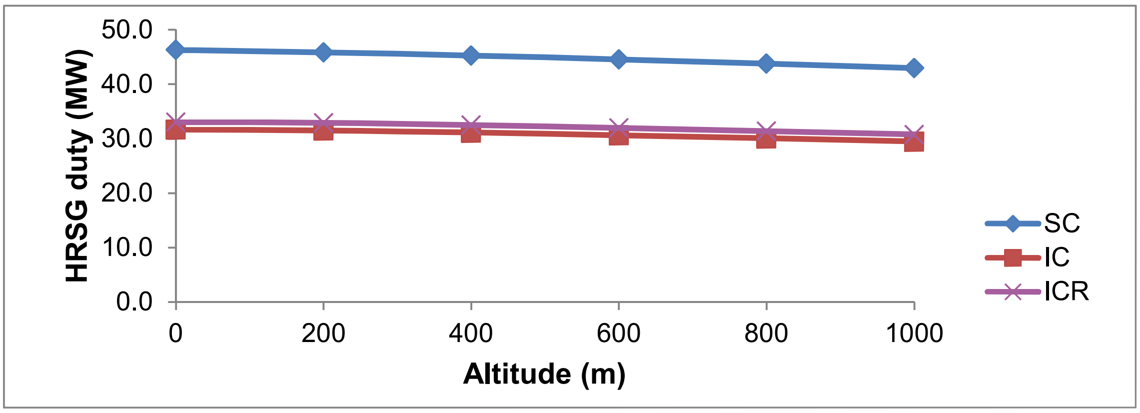

Figure 5-14 Variation of HRSG duty with altitude for the LS1-ADIGT-CHP

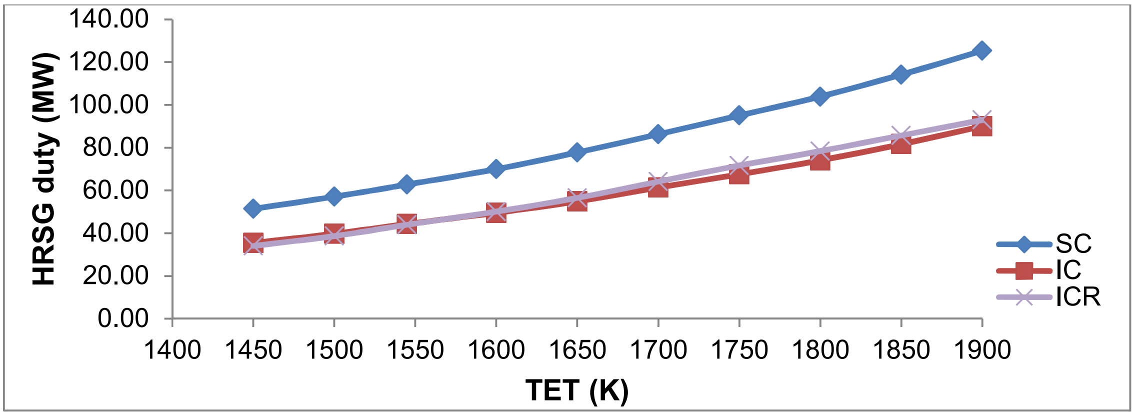

Figure 5-15 Variation of HRSG duty with TET for the LS2-ADIGT-CHP

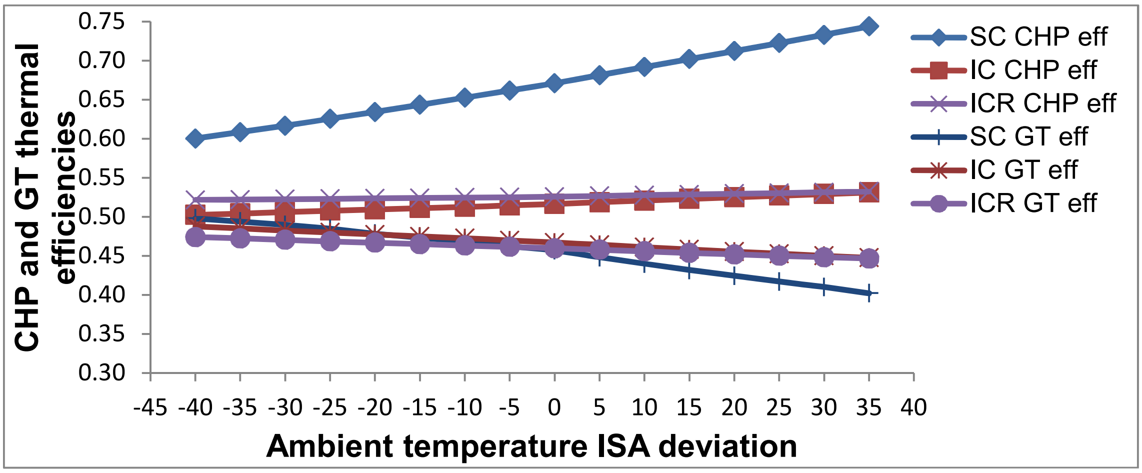

Figure 5-16 Effect of ambient temperature on CHP and GT efficiencies for the LS2-ADIGT-CHP

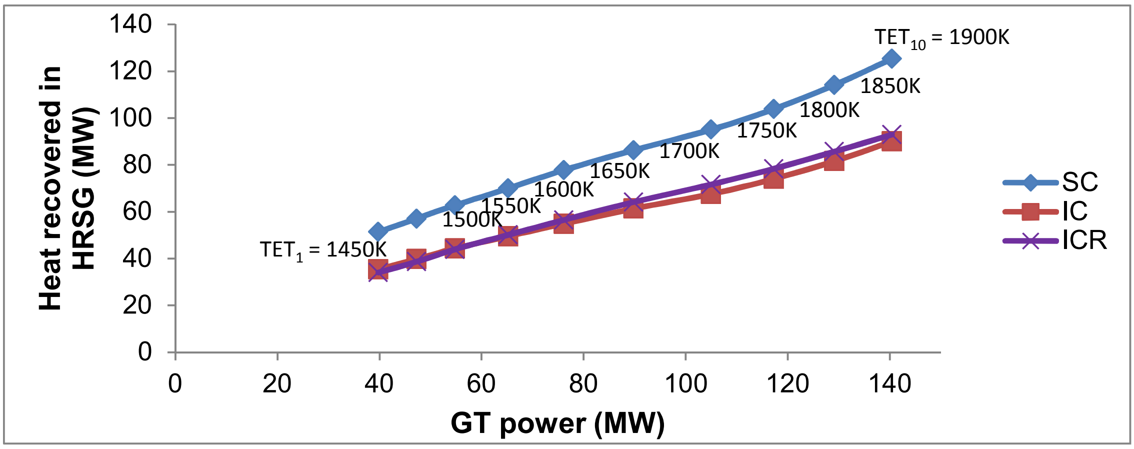

Figure 5-17 Variation of HRSG duty with GT power at increasing TET (LS2-ADIGT-CHP)

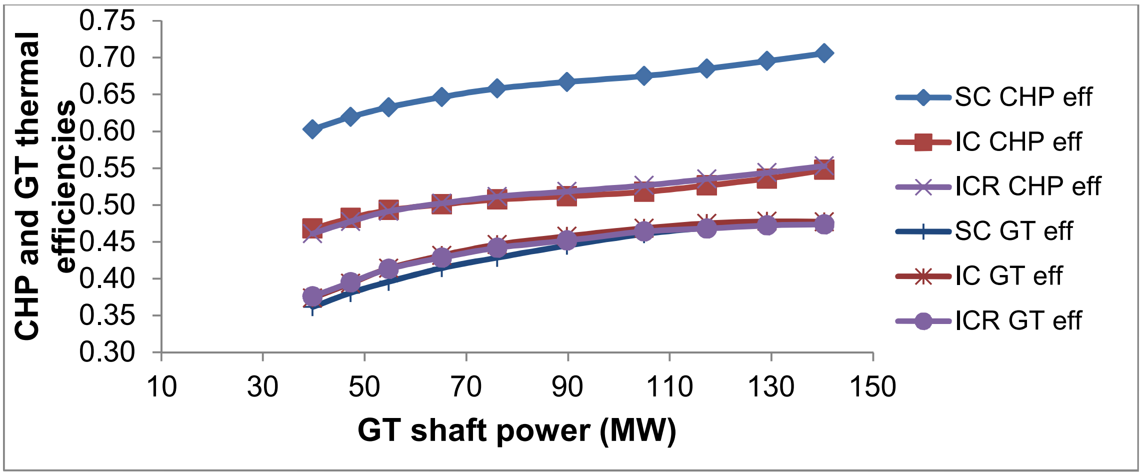

Figure 5-18 Effect of GT power on CHP and GT efficiencies at increasing TET (LS2-ADIGT-CHP)

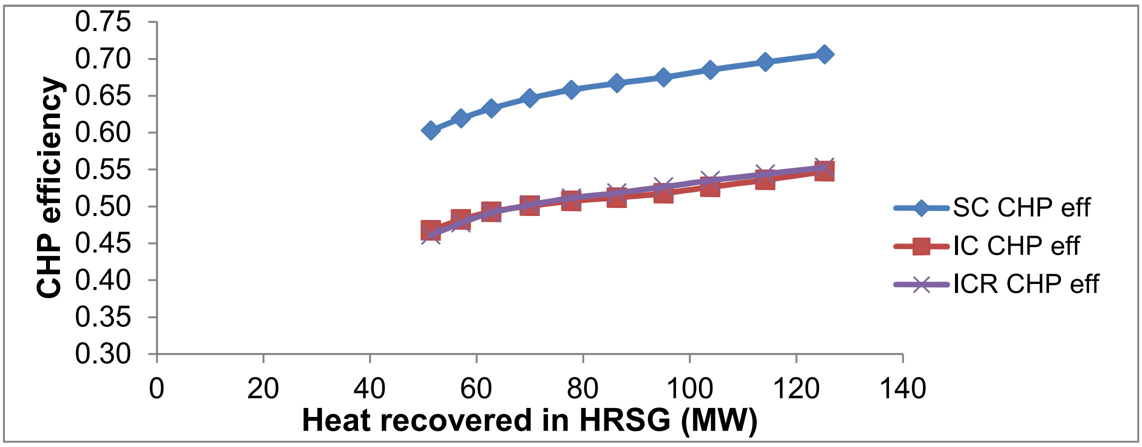

Figure 5-19 CHP efficiency varying with HRSG duty at increasing TET (LS2 ADIGT-CHP)

The LS1 and LS2 aero-derivative engines are observed to perform in similar trend in CHP application. As presented in Figure 5-13, Figure 5-16 , and Figure 5-18, CHP efficiency actually increases with increasing TET, ambient temperature, GT power, and HRSG duty in all cycle configurations in this category of ADIGT-CHP. The SC is observed to show higher CHP efficiency than the IC and ICR CHP, whereas there is no much difference in CHP efficiencies of IC and ICR cycles. The superior performance of SC CHP is as a result of its higher HRSG duty due to its higher exhaust gas temperature compared to others. Although less fuel is utilised in the advanced cycles than the SC, the decrease in combustor heat rate in the advanced cycles is minute compared with the huge increase in exhaust gas temperature and steam rate of the SC CHP.

Furthermore, the heat-to-power ratio is observed to be least in the IC cycle than SC and ICR, and highest in the SC cycle at both DP and OD conditions. This is shown in Figure 5-17. In essence, this means that given a range of power output at any condition of TET and ambience, the SC cycle would generate more steam than the IC and ICR, while IC would generate the least steam rate. This is due to the fact that GT exhaust gas temperature is highest in the SC cycle and exits the HRSG at the least temperature. This creates huge drop in temperature of exhaust gas from exit of GT to exit of HRSG in the SC cycle. This exhaust gas temperature drop is smaller in ICR cycle and least in IC cycle. Hence, huge amount of heat is extracted from exhaust gas in SC cycle than IC and ICR at same conditions. Besides, at same conditions of TET as plotted in Figure 5-17, SC cycle generates more HRSG duty than the advanced cycles because it consumes more fuel, and excess fuel in turn increases GT exhaust gas temperature, which leads to the large temperature drop in the HRSG.

5.6 Chapter summary

The following are described in this chapter:

- Petrochemical/refinery industry processes that utilise steam for process heating are defined and briefly discussed.
- Methodology of CHP performance modelling and analysis is described
- Modelling of HRSG and CHP performances by the application of pinch and approach point technology are carried out.
- DP and OD performance analyses of SS-, LS1-, and LS2-ADIGT-CHP are done.
- For the SS-ADIGT-CHP, better CHP efficiency is exhibited by the RC and ICR cycles than the SC engine. Also, the RC engine produces the highest HRSG duty.
- For both LS1-ADIGT-CHP and LS2-ADIGT-CHP, the SC exhibits the highest CHP efficiency and HRSG duty than the IC and ICR engine cycles.

6 TERA METHODOLOGY FOR ADIGT-CHP IN THE PETROCHEMICAL INDUSTRY

6.1 Overview

Techno-economic and environmental risk analysis (TERA) framework as a multi-disciplinary decision-making tool is adapted here to assess the economic viability of utilising aero-derivative gas turbines combined-heat-and-power generation in the petrochemical industry. TERA framework comprises a network that combines the following modules: engine technical performance module, emission and environment module, economic and risk modules. In this chapter the formulation and development of the economic module of TERA for ADIGT-CHP is presented, and other various modules are highlighted.

6.2 Engine performance module

This module of TERA has been dealt with and implemented in chapters 4 and 5. It involved the application of TURBOMATCH in the preliminary DP and OD performance analysis of the various categories of aero-derivative engine cycles. Also, it was implemented in the combined-heat-and-power DP and OD performance analysis. The outputs of these technical performances are recalled as inputs to the emissions, and economic modules.

6.3 Emissions and environment module

This module calculates the total amount of emissions produced as products of combustion that occur in the engine over the range of design point and off-design performance. These combustion products include oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), and water vapour (H_2O_{vap}). This TERA module was implemented in section 4.4 , where NO_x, CO, CO_2, and H_2O_{vap} emissions indices of the ADIGT were estimated using HEPHAESTUS code.

6.4 Economic evaluation module

Economic return drives investment in any new equipment, of which CHP is not an exception. TERA tool is useful in predicting the future and reducing the risk of investing in new equipment. This module receives inputs from engine performance, and emissions modules. For a CHP scheme to be adjudged worthwhile it has to be profitable than the base load case assessment. The base load case is defined as the use of on-site boiler to satisfy required steam demand of a site while the site power demand is met by purchasing Grid electricity (Carbon Trust, 2010).

The Department of Energy and Climate Change (DECC), UK outlines some parameters used in the economic appraisal of CHP schemes as: simple payback period (SPBP), net present value (NPV), and internal rate of return (IRR) (DECC, 2012). These capabilities are captured as contents of the **economic model** developed here in this research. A discounting technique based on NPV method is presented to allow an initial assessment of the likelihood of various engine cycles being attractive in a specific situation of CHP application.

6.4.1 Payback period and break-even point

Simple payback period (SPBP) is the length of time usually in years taken to recover the initial investment capital of implementing the CHP scheme based on the annual savings realised. It excludes salvage value (Milton and Lucas, 2010). Equation 6-1 is used to calculate SPBP.

$$\text{SPBP (in years)} = \frac{Capital\ investment\ cost\ of\ CHP}{Annual\ savings\ from\ CHP\ over\ conventional\ case}$$ **Equation 6-1**

Where,

$$\text{Capital investment cost of CHP} = \text{total installation cost of the CHP plant}$$

$$\text{Annual savings} = \text{conventional base case annual total running cost} - \text{CHP case annual total running cost}$$

$$= \text{conventional base case annual total cost of energy, operation and maintenance} - \text{CHP case annual total cost of energy, operation and maintenance}$$

Break-even point is the level of product sales at which financial revenues equal total costs of production; at higher volume of sales financial profits are made (Khatip, 2014). Thus, a CHP project is said to have break-even when the sum of saved energy costs and energy export sales equals the capital/installation cost or investment cost of the CHP plant.

6.4.2 Net present value

The difference between the present worth of all expenses and the present worth of all revenues during the life cycle of a CHP is termed net present value (NPV). It includes savings, and is the present worth of the total net cash flow of the CHP investment. It is calculated using Equation 6-2 or Equation 6-3

$$NPV = -F_0 + \sum_{t=0}^{N} \frac{F_t}{(1+d_t)^t}$$ **Equation 6-2**

Or

$$NPV = -F_0 + \sum_{t=0}^{N} \frac{F_t}{(1+d)^t}$$ **Equation 6-3**

Where

d_t = the market interest rate or market discount rate during the period t, and when it is considered constant d_t = d.

N = the period in time for which the investment is assumed to operate (the life of the project). Time period in years is usually used, though day, month, six-month, can be used.

F_t = net cash flow in year t (revenue + savings – expenses). The term “net cash flow” here could be negative, which would indicate loss in year t.

F_0 = the present worth of the investment (at time = 0), and it is negative. It is equal to the capital cost.

There are three possible solutions:

NPV > 0; → return on investment (RoI) > d; → economically viable investment with profit, given condition (N, d)

NPV = 0; → return on investment (RoI) = d; → economically viable investment without neither profit nor loss, given condition (N, d)

NPV < 0; → return on investment (RoI) < d; → investment is not economically viable with loss under the given specification (N, d) (EDUCOGEN, 2001).

6.4.2.1 Algorithm for computing the net present value of CHP

- **Initial cash flow (F_0, t = 0):** This is given by Equation 6-4

$$\mathbf{F_0} = C_g + L + C$$ **Equation 6-4**

Where, C = investment cash at hand, C_g = investment grant, L = loan

F_0 may comprise of only C_g or L or C, and it is the capital cost of CHP installation.

- **Net cash flow for N years (F_t, t = 1 to N)**

Annual operation savings (f_t): This is given by Equation 6-5

$f_t = (C_e + R_e + C_h + R_h - C_{Ge} – C_{Bh} - C_f - C_{o/m} - C_{emtx})$ **Equation 6-5**

Where, C_e = avoided cost of electricity = cost of electricity that would be purchased from the grid, if not cogenerated.

R_e = revenue from selling excess electricity, if any.

C_h = avoided cost of heat, i.e. cost of heat that, if not cogenerated, would be produced by boiler(s).

R_h = revenue from selling excess steam, if any.

C_{Ge} = cost of electricity purchased from the grid during outages of on-site generation.

C_{Bh} = cost of heat produced by boiler(s) during outages of CHP.

C_f = cost of fuel for the cogeneration system = fuel consumed x fuel tariff.

$C_{o/m}$ = operation and maintenance cost (except fuel) of the cogeneration system.

C_{emtx} = emission tax

Subscript t = the year (t = 1, 2,..., N) during which investment lasts.

Assumptions:

The operation of the plant starts from the beginning of the first year, t = 1.

Construction period is assumed as year t = 0 which takes capital cost F_0

A life period of 20 years (say 2013 - 2032) is chosen, (that is N = 20).

Annual net cash flow (F_t): This is given by Equation 6-6

$F_t = f_t — A_{Lt} — r_T\, T_t + SV_N$, for (t = 1, 2, ..., N) **Equation 6-6**

Where, F_t = net cash flow in year t,

f_t = operation saving in year t,

A_{Lt} = equal yearly payments of principal and interest for repayment of loan,

r_T = tax rate,

T_t = taxable income in year t, due to cogeneration,

SV_N = salvage value of the investment at the end of the economic life cycle, i.e. at the end of year N.

Assumptions:

Operation savings is main target of CHP, hence, T_t = 0

Assuming the scenario where savage value is used completely for disposal of plant as scrap, a worse case scenario. SV_N = 0.

- **NPV:**

Then applying Equation 6-3

$NPV = -F_0 + \sum_{t=1}^{N} \frac{F_t}{(1+d)^t}$ where 0 ≤ NPV ≥ 0

Assumptions:

Total life-cycle of CHP plant (N) = 20 years

Discount rate (d) = 10%

Electricity tariffs escalation rate = 5%

Heat tariffs escalation rate = 5%

Fuel price escalation rate = 5%

Operation & maintenance cost escalation rate = 3%

Emission tax escalation rate = 3%

Interest on loan = 5%

Loan repayment period = 10 years

Loan holiday = 2 years

Availability of on-site generation plant is approximately 95% of yearly hours.

(Nkoi et al, 2014; Polyzakis, 2006)

6.4.3 Internal rate of return

Internal rate of return is the discount rate that results in an NPV value of zero. This implies that IRR is the discount rate that makes the net present worth of future cash flows equal the CHP capital investment cost. An iterative method employing Equation 6-7 is used to determine IRR (EDUCOGEN, 2001).

Internal rate of return, IRR = d, for NPV = 0;

$$\rightarrow 0 = -F_0 + \sum_{t=1}^{N} \frac{F_t}{(1+IRR)^t}$$ **Equation 6-7**

Figure 6-1 shows the flow chart for computing NPV and IRR

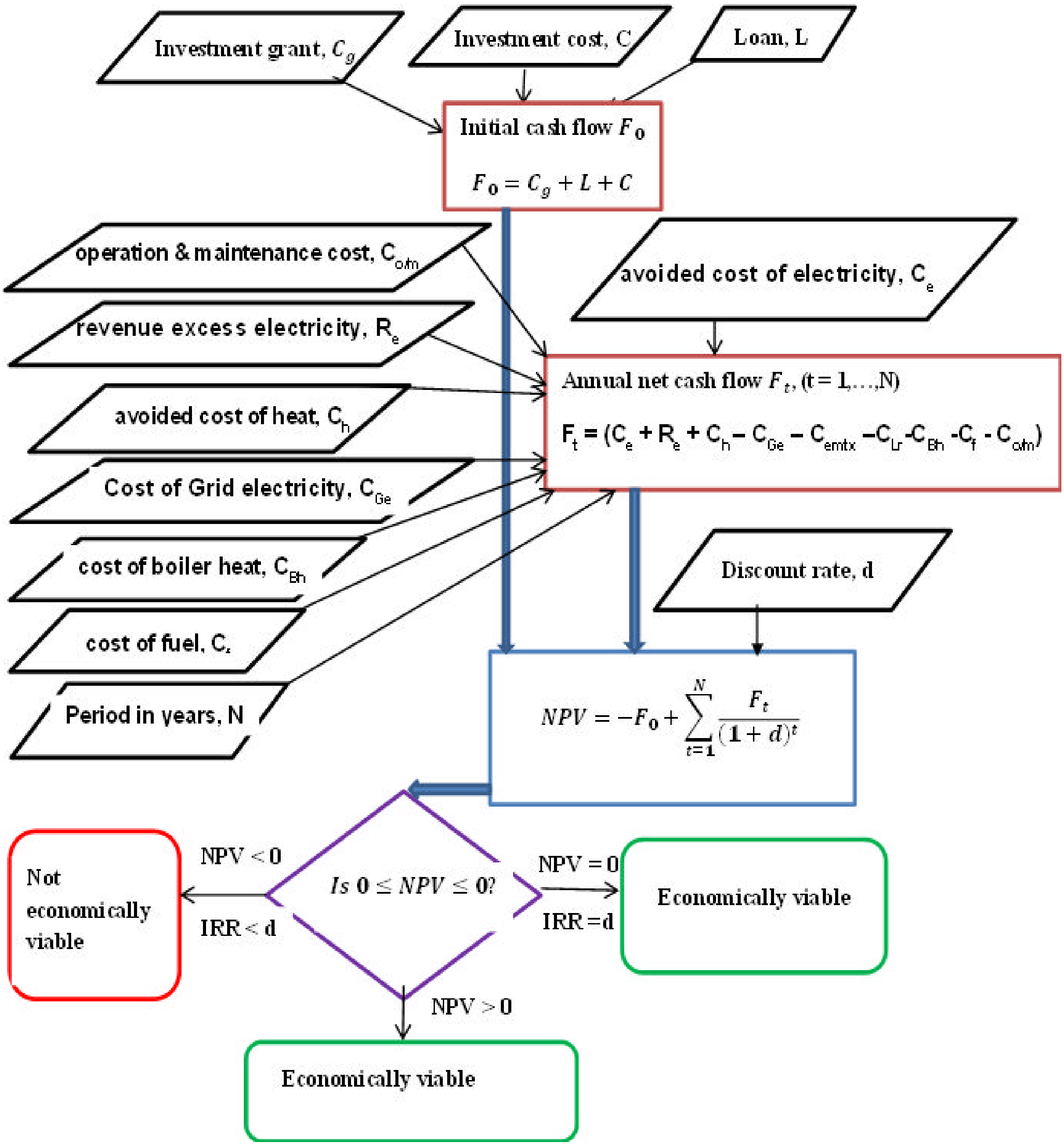

Figure 6-1 Flow chart for NPV computation (Nkoi et al, 2014)

Limitation of model:

This model does not account for depreciation of plant as salvage value is assumed to be the cost of disposal of scrap plant.

6.4.4 Discount rate

Discount rate is the factor used to equate the future value of money to its present worth. It defines the long term opportunity cost of capital invested. The return on investments forfeited elsewhere by committing capital to a project under consideration defines opportunity cost of capital (Khatib, 2014). The high the discount rate, the more the future worth of money is being discounted to its present value.

6.4.5 Escalation rate

Escalation may be defined as changes in the levels of prices caused by prevailing economic conditions (Hollmann and Dysert, 2007). Changes in productivity, technology, market demand, supply, labour shortage, and profit margin influence price escalation. Escalation rate is the market rate at which cost of items increase annually. It may vary from item to item and depends largely on the country and zone where items are marketed. In CHP, escalation applies to cost of fuel, electricity, operation/maintenance, and emission tax.

6.4.6 Investment/capital cost

Capital cost of investment refers to the total cost incurred in construction/installation of the CHP plant. This includes:

- Equipment cost: This cost entails purchase of equipment, inclusive of taxes, and transportation. The cost depends on the system components and specifications. This equipment consist mostly the prime mover and generator set.
- Installation costs: This consists of Installation permits, Land acquisition and preparation, Building construction, Installation of equipment, documentation and as built drawings. Grid connections, including reinforcement of local/national electricity networks. First set of spare parts and any special tools needed for servicing and repair.
- "Soft" costs: construction management fees, legal fees, environmental studies, training, additional costs may incur under certain financial arrangements (e.g. debt insurance, bank fees, and interest paid during construction), Architectural and engineering design fees, permitting costs, special consultants and inspectors (EDUCOGEN, 2001; Stromberg et al, 1993).

Department of Energy and Climate Change has specified rates of Installation/capital cost of GT CHP per kW power output (DECC, 2013). In addition, Table 6-1 presents estimated equipment and installation costs for five typical gas turbine CHP systems, and Table 6-2 shows a number of cost adders that aggravates the cost of gas turbine power systems (Energy and Environmental Analysis, 2008).

Table 6-1 Estimated capital costs for typical gas turbine-based CHP systems (Energy and Environmental Analysis, 2008)

Cost Component	*System 1*	System 2	System 3	System 4	System 5
Nominal Turbine Capacity (MW)	1	5	10	25	40
	Equipment (Thousands of 2007 $)				
Combustion Turbines	$1,015	$2,733	$6,102	$12,750	$23,700
Electrical Equipment	$411	$540	$653	$1,040	$1,575
Fuel System	$166	$177	$188	$251	$358
Water Treatment System	$74	$180	$293	$370	$416
Heat Recovery Steam Generators	$508	$615	$779	$1,030	$1,241
SCR, CO, and CEMS	$0	$0	$0	$0	$0
Building	$0	$0	$0	$0	$0
Total Equipment	$2,173	$4,246	$8,015	$15,440	$27,290
Construction	$769	$1,402	$2,568	$4,947	$8,744
Total Process Capital	$2,942	$5,648	$10,583	$20,387	$36,034
Project/Construction Management	$271	$402	$664	$1,279	$2,260
Shipping	$47	$89	$164	$317	$559
Development Fees	$217	$425	$802	$1,544	$2,729
Project Contingency	$116	$177	$276	$532	$940
Project Financing	$230	$431	$799	$1,540	$2,721
Total Plant Cost	$3,822	$7,172	$13,288	$25,598	$45,243
Actual Turbine Capacity (kW)	1,150	5,457	10,239	23,328	46,556
Total Plant Cost per net kW (2007 $)	$3,324	$1,314	$1,298	$1,097	$972

Table 6-2 Capital cost adders for complex installations and additional equipment (Energy and Environmental Analysis, 2008)

Cost Component	*System 1*	System 2	System 3	System 4	System 5
Nominal Turbine Capacity (MW)	1	5	10	25	40
Complex Installation Cost Adder with no additional equipment (2007$ 1000)	$489	$864	$1,551	$2,987	$5,280
	Additional Equipment				
Building	n.a.	$311	$414	$576	$759
Compressor Incremental Cost (2007$	$416	$937	$1,182	$1,223,500	$1,797,90
1000) Compressor Power Use (kW)	9	90	203	500	0

Cost Component	*System 1*	System 2	System 3	System 4	System 5
SCR Incremental Cost (2007$	$397	$732	$986	$1,350	$1,743
1000) SCR Power Use (kW)	6	29	53	120	225
Equipment Cost Multipliers[15]					
Normal Installation	176%	169%	166%	166%	166%
Multiplier Complex	198%	189%	185%	185%	185%
Basic and Complex Cost Estimate Range 2007 $/kW					
Basic Capital Cost 2007 $/kW	$3,324	$1,314	$1,298	$1,097	$972
Complex Installation Capital Cost 2007 $/kW	$5,221	$2,210	$1,965	$1,516	$1,290

6.4.7 Energy cost (fuel and grid power)

Energy cost of a CHP comprises cost of fuel and Grid electricity purchased. Electricity and fuel cost are given in price per unit power consumption, such as p/kWh. Total cost of electricity purchased is obtained by Equation 6-8, whereas fuel cost is given by Equation 6-9.

Electricity cost C_{Ge} = electricity tariff p/kWh x kWh of electricity consumed **Equation 6-8**

Fuel cost C_f = Gas tariff p/kWh x kWh of power generated **Equation 6-9**

Typical rates of energy cost are given in Table 6-3 (DECC, 2012).

Table 6-3 Prices of fuel purchased by industrial customers in the UK including climate change levy (Source: DECC survey of energy suppliers)

Fuel	Size of consumer	Pence per kWh								
		2010	2011				2012			
		4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter
Electricity	Very Small	12.23	11.36	11.74	12.11	13.37	12.54	12.35r	12.73	12.92
	Small	9.99	10.06	9.97	10.17	10.64	10.78	10.65	10.98	10.94
	Small/ Medium	8.43	8.46	8.61	8.79	9.32	9.45	9.40	9.57	9.68
	Medium	7.58	7.77	7.74	7.81	8.33	8.46	8.54	8.65	8.77
	Large	6.76	7.15	7.48	7.32	7.62	8.02	8.39	8.01	8.39
	Very Large	6.77	7.22	7.25	6.86	7.36	7.00	7.96	7.82	8.23
	Extra Large	6.46	7.02	6.70	7.11	7.39	7.76	8.08	7.99	8.43
	Average	8.42	8.42	8.37	8.44	9.00	9.22	9.16	9.14	9.46
Gas	Very Small	2.973	3.251	3.517	3.427	3.687	3.728	3.867	3.936	3.751
	Small	2.292	2.393	2.545	2.647	2.930	2.885	2.951	2.915	2.850
	Medium	1.973	2.098	2.208	2.125	2.570	2.546	2.574	2.461	2.676
	Large	1.887	1.998	2.133	2.001	2.386	2.335	2.272	2.124	2.410
	Very Large	1.866	1.986	2.122	1.959	2.127	2.081	1.950	2.042	2.215
	Average	2.144	2.298	2.374	2.222	2.646	2.645	2.583	2.446	2.705

6.4.8 Operation and maintenance cost (fixed and variable)

Operation and maintenance cost comprises of fixed O&M cost and variable O&M cost. Variable O&M cost include cost of maintenance of auxiliary equipment (generator, gas compressor etc.), maintenance of the prime mover/electrical generator, consumables, labour, and administration. Typical rates of variable and fixed O&M cost for GT and CHP are presented in Table 6-4 and Table 6-5.

Table 6-4 Typical rates for CHP O&M cost (DECC, 2013)

	4500 operating hours/year	8000 operating hours/year
Gas turbine	0.4 p/kWh	0.35 p/kWh
Gas engine	0.7 p/kWh	0.6 p/kWh
Dual-fuel compression ignition engines	0.8 p/kWh	0.7 p/kWh
Steam turbines	< 0.05 p/kWh	< 0.05 p/kWh

Guides to unit prices and cost estimations of CHP and GT installations, electricity, gas fuel, operations and maintenance, and emissions tax, were obtained from public domain references (Greenpeace, 2008; Energy and Environmental Analysis, 2008; HM Revenue & Customs DECC, 2011; DECC, 2013; US EIA, 2013).

6.4.9 Loan repayment

Equal annual loan repayment is calculated using Equation 6-10 (Gutierrez and Dalsted), given an interest rate r, and loan duration of N years.

$$C_{Lr} = (L * r)/[1 - (1 + r)^{-N}] \qquad \text{Equation 6-10}$$

Where C_{Lr} = equal annual loan repayment, and L = loan

Table 6-5 Updated estimates of power plants capital, operation and maintenance costs (Source: US EIA, 2013)

	Plant Characteristics		Plant Costs (2012$)			
	Nominal Capacity (MW)	Heat Rate (Btu/kWh)	Overnight Capital Cost ($/kW)	Fixed O&M Cost ($/kW-yr)	Variable O&M Cost ($/MWh)	NEMS Input
Coal						
Single Unit Advanced PC	650	8,800	$3,246	$37.80	$4.47	N
Dual Unit Advanced PC	1,300	8,800	$2,934	$31.18	$4.47	Y
Single Unit Advanced PC with CCS	650	12,000	$5,227	$80.53	$9.51	Y
Dual Unit Advanced PC with CCS	1,300	12,000	$4,724	$66.43	$9.51	N
Single Unit IGCC	600	8,700	$4,400	$62.25	$7.22	N
Dual Unit IGCC	1,200	8,700	$3,784	$51.39	$7.22	Y
Single Unit IGCC with CCS	520	10,700	$6,599	$72.83	$8.45	N
Natural Gas						
Conventional CC	620	7,050	$917	$13.17	$3.60	Y
Advanced CC	400	6,430	$1,023	$15.37	$3.27	Y
Advanced CC with CCS	340	7,525	$2,095	$31.79	$6.78	Y
Conventional CT	85	10,850	$973	$7.34	$15.45	Y
Advanced CT	210	9,750	$676	$7.04	$10.37	Y
Fuel Cells	10	9,500	$7,108	$0.00	$43.00	Y
Uranium						
Dual Unit Nuclear	2,234	N/A	$5,530	$93.28	$2.14	Y
Biomass						
Biomass CC	20	12,350	$8,180	$356.07	$17.49	N
Biomass BFB	50	13,500	$4,114	$105.63	$5.26	Y
Wind						
Onshore Wind	100	N/A	$2,213	$39.55	$0.00	Y
Offshore Wind	400	N/A	$6,230	$74.00	$0.00	Y
Solar						
Solar Thermal	100	N/A	$5,067	$67.26	$0.00	Y
Photovoltaic	20	N/A	$4,183	$27.75	$0.00	N
Photovoltaic	150	N/A	$3,873	$24.69	$0.00	Y
Geothermal						
Geothermal – Dual Flash	50	N/A	$6,243	$132.00	$0.00	N
Geothermal – Binary	50	N/A	$4,362	$100.00	$0.00	N
Municipal Solid Waste						
Municipal Solid Waste	50	18,000	$8,312	$392.82	$8.75	N
Hydroelectric						
Conventional Hydroelectric	500	N/A	$2,936	$14.13	$0.00	N
Pumped Storage	250	N/A	$5,288	$18.00	$0.00	N

6.4.10 Energy demand (power and heat)

To implement economic evaluation of a CHP project, the energy demand in terms of electrical power and heat (steam) consumption on site must be ascertained. In selecting CHP plant, decision must be taken whether to match electricity demand and have surplus/deficit of heat or match heat demand and have surplus/deficit of electricity depending on power to heat ratio. The energy demand (consumption) of the plant is reported for a given period of time usually a year where records are kept on daily and monthly bases. Also, information about the number of hours of power plant operation and the number of hours of outages must be known. Energy generation and consumption of a plant vary with seasons of the year (winter, spring, autumn, summer) and with daily ambient temperatures depending on regions and countries. Energy consumed in form of electricity and heat are defined by Equation 6-11 and Equation 6-12 respectively.

$$\text{Power consumed(kWh)} = \text{GT power output (kW)} \times \text{time (hours)} \qquad \text{Equation 6-11}$$

$$\text{Heat consumed(kWh)} = \text{HRSG duty (kW)} \times \text{time (hours)} \qquad \text{Equation 6-12}$$

6.4.11 Climatic data

As stated in earlier section power generated from power plants varies according to seasons of the year and daily temperatures depending on regions. This implies that climatic conditions of the site of CHP will affect its operation and hence its economics. The performance of CHP plant with respect to prevailing ambient condition of temperature is very important. Therefore, climatic data of the CHP site must be known when carrying out performance analysis.

6.5 Risk module

There is high level of uncertainty that underlie any future prediction. The tendency that input parameters such as fuel price or electricity tariff used in the techno-economic evaluation of a given project may vary over time is pertinent. This would pose enormous risk to investment in the project. To carry out risk analysis of the model output like NPV, values of inputs are sampled randomly from a cumulative frequency distribution. Such inputs probability distributions include the likes of normal distribution, triangular distribution, rectangular distribution, etc. Several methods of random sampling from input probability distributions exist such as Monte Carlo sampling technique, and Latin Hypercube sampling method (Khan et al, 2011; Vose, 2008). These are computer simulation techniques employed to determine the probability effect of variation of the input parameters on predicted output. Also, the sensitivity of the output parameter to the changes in input parameters could be analysed.

In this research, for instance, the NPV that would be predicted of an engine cycle CHP may not be certain based on uncertainty of prevailing cost values of grid electricity or fuel used in its computation. Thus thousands of random values of each of such input parameters are generated in a probabilistic model simulation with deviations from the mean value used. By so doing, probability of a wide range of NPV values occurring is forecasted that would offer an investor a better view of the profitability of the project. A software called @Risk 6.0 is deployed in this research as add-in to the techno-economic model to implement the risk module, and to carry out sensitivity analysis of NPV (Palisade Corporation, 2013). The cumulative frequency distribution random sampling technique employed in @Risk 6.0 is the Latin Hypercube sampling method.

6.5.1 Cumulative frequency distribution

According to Palisade Corporation (author of @Risk), it is usually helpful to first understand the principle of a cumulative distribution, when studying different sampling methods. All probability distributions could be expressed in cumulative pattern. A scale from 0 to 1 on the vertical-axis typifies any cumulative curve, with vertical-axis values representing the cumulative probability corresponding to horizontal-axis value.

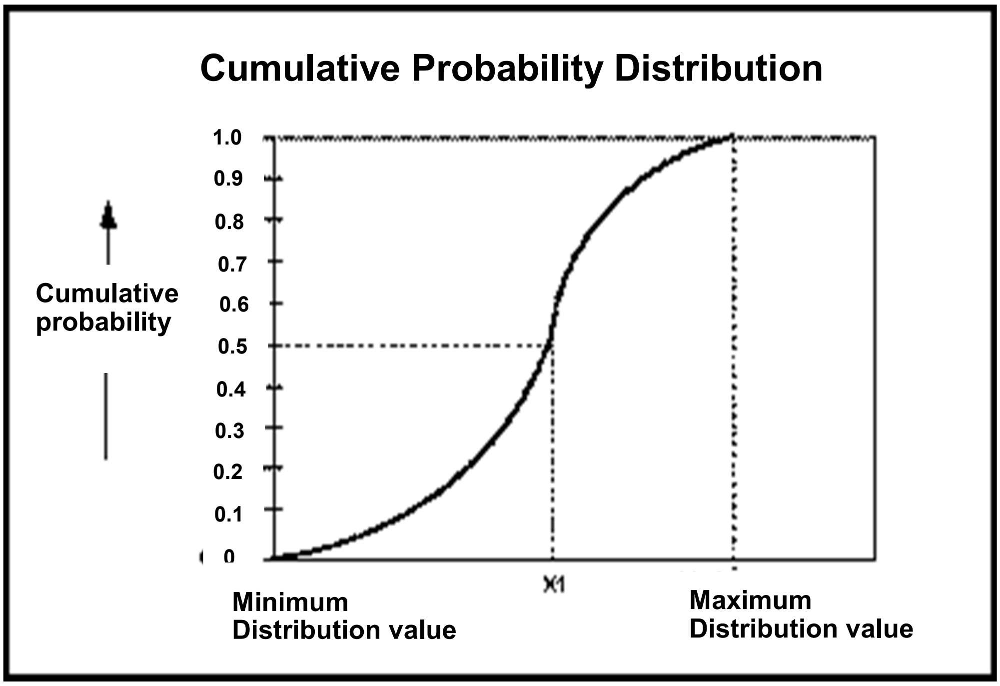

Figure 6-2 Cumulative probability distribution (Source: Palisade Corporation, 2013)

Figure 6-2 illustrates a cumulative curve where the 0.5 cumulative value is the point of 50% cumulative probability (0.5 = 50%). 50% of the values in the distribution fall below this median value and 50% are above. The 0 cumulative value is the minimum value (0% of the values will fall below this point) and the 1.0 cumulative value is the maximum value (100% of the values will fall below this point). This cumulative curve is so important to understanding sampling.

This is because the 0 to 1.0 scale of the cumulative curve is the range of the possible random numbers generated during sampling, and in a typical Latin Hypercube or Monte Carlo sampling sequence, the computer will generate a random number between 0 and 1 - with any number in the range equally likely to occur. This number is then used to select a value from the cumulative curve. In the example of Figure 6-2, the value sampled for the distribution shown would be X1 if a random number of 0.5 was generated during sampling. Since the shape of the cumulative curve is based on the shape of the input probability distribution, it is more probable that more likely outcomes will be sampled. The more likely outcomes are in the range where the cumulative curve is the steepest (Palisade Corporation, 2013).

6.5.2 Random sampling from input distribution

An output variable is defined by a function or set of functions given one or more uncertain input variables. The set of functions could describe the interdependence between different inputs and interdependence over time. This defined function forms a model to be studied for instance of the NPV of an investment project. Next, a probability distribution is specified for a range of values for the uncertain input variable(s). There are various types of probability distributions that are used, namely normal, triangular, uniform or rectangular, step rectangular, trapezoidal, distributions etc (Khatip, 2014; Palisade Corporation, 2013).

Latin Hypercube simulation method and Monte Carlo analysis technique work by generating random samples for the input distributions of a model. Consider the distribution of an uncertain input variable x. Let F(x) be the cumulative distribution function of x which defines the probability P that the variable X will be less than or equal to x. This probability function is given by Equation 6-13.

$$\mathrm{F(x)} = \mathrm{P(X \leq x)} \qquad \text{Equation 6-13}$$

This would mean that $0 \leq \mathrm{F(x)} \leq 1$

Now, Equation 6-13 could be looked in the reverse direction: for a given value of x what is the value of F(x)?. Let this inverse function be G(F(x)), then this is defined in Equation 6-14 .

$$\mathrm{G(F(x))} = \mathrm{x} \qquad \text{Equation 6-14}$$

It is this concept of the inverse function G(F(x)) that is employed to generate random samples from each distribution in a risk analysis model (Vose, 2008). The graphical representation of the relationship between F(x) and G(F(x)) is illustrated in Figure 6-3.

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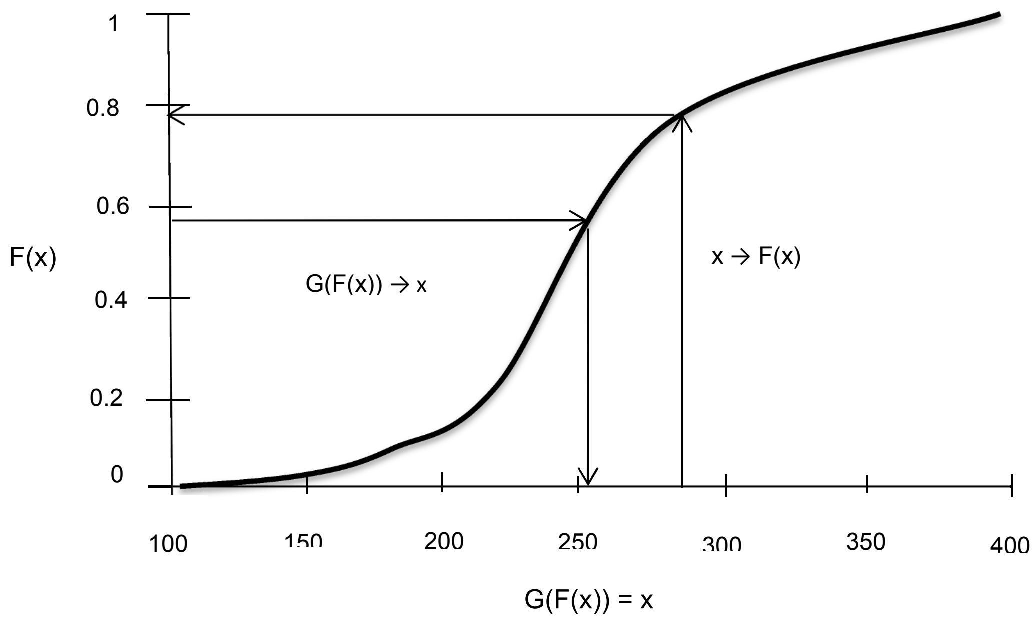


Figure 6-3 The relationship between x, F(x) and G(F(x)) (source: Vose, 2008)

A random number say r is generated between 0 and 1 in order to generate a random sample for a probability distribution. This value is then inputted into the equation to determine the value to be generated for the distribution as defined by Equation 6-15 .

$$\mathrm{G(r) = x} \qquad \text{Equation 6-15}$$

The random number r is generated from a Uniform(0,1) distribution to provide equal opportunity of an x value being generated in any percentile range.

It is not always possible for some types of probability distribution to determine an equation for G(F(x)), in which case numerical solving techniques are usually used.

@Risk 6.0 employs the inverse function concept in Latin Hypercube sampling method and allow the user to control how the distribution is sampled via its Uniform(0,1) distribution. For example in case of normal distribution in @Risk: Normal(μ, σ, RiskUniform(0,1)), where μ is mean and σ is the standard deviation of the normal distribution, returning the range of 0^{th} to 100^{th} percentiles of the distribution (Vose, 2008).

6.5.3 Latin Hypercube sampling technique

Latin Hypercube sampling is more like a modified Monte Carlo method. According to Palisade Corporation, Latin Hypercube sampling is a recent development in sampling technology, formulated to accurately reproduce the input distribution through sampling in fewer iterations when compared with the Monte Carlo method. The basis of Latin Hypercube sampling is stratification of the input probability distributions. Stratification partitions the cumulative curve into equal intervals on the cumulative probability scale - 0 to 1.0. A sample is then randomly taken from each interval or stratification of the input distribution. Sampling is made to represent values in each interval, and so, is made to reproduce the input probability distribution.

In the illustration of Figure 6-4, the cumulative curve has been divided into 5 intervals. During sampling, a sample is drawn from each interval as against 5 close clustered samples that would be drawn using Monte Carlo method. With Latin Hypercube, the samples are better spread over the entire range of the distribution, thereby accurately reflect the distribution of values in the input probability distribution.

The method of “sampling without replacement” is being used in Latin Hypercube sampling. The number of stratifications of the cumulative distribution is equal to the number of iterations performed. In the example of Figure 6-4, there were 5 iterations and thus 5 stratifications were made to the cumulative distribution. A sample is taken from each stratification. However, once a sample is taken from a stratification, this stratification is not sampled from again - its value is already represented in the sampled set. Sampling within a given stratification occur in @Risk 6.0 by the programme choosing a stratification for sampling, then randomly chooses value from within the selected stratification (Palisade Corporation, 2013).

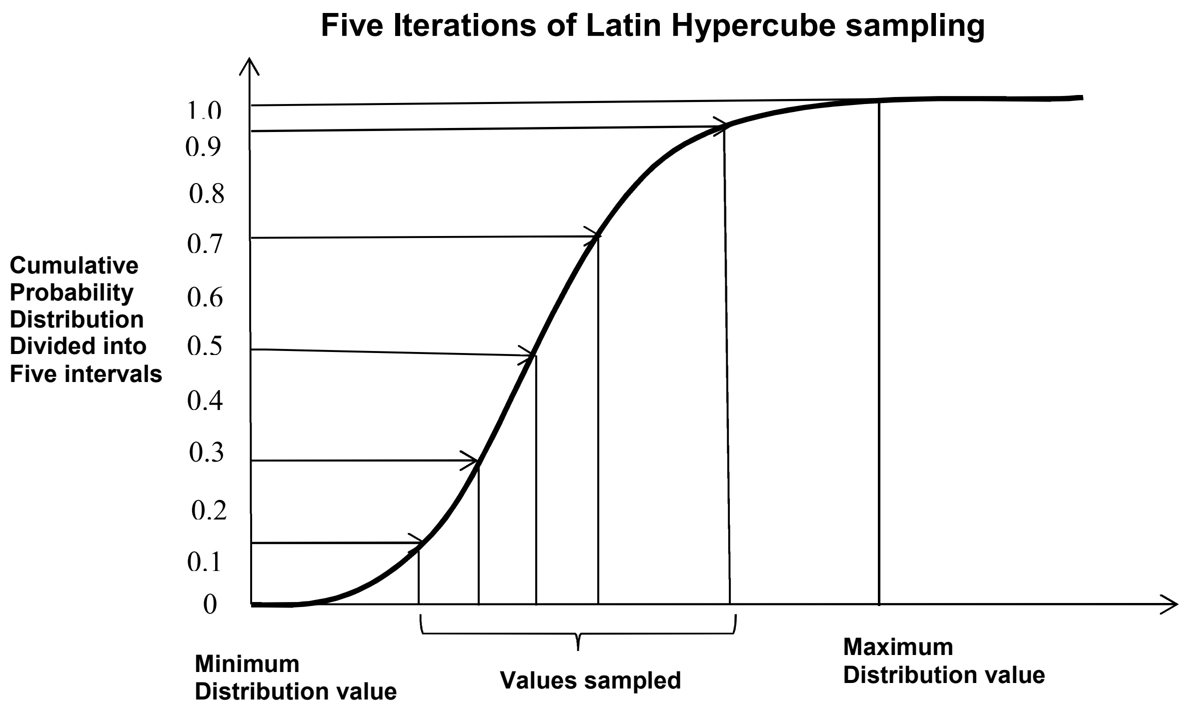


Figure 6-4 Latin Hypercube sampling technique
(Source: Palisade Corporation, 2013)

6.5.4 Probability distributions

Probability distributions are used in @Risk 6.0 to handle the uncertainty present in the variables in a model. Probability distributions are used to describe the range of possible values for uncertain elements in the model and are entered using probability distribution functions. Several probability distribution functions exist but only three are considered in this work, namely, triangular, uniform or rectangular, and normal, distributions. These three types of cumulative probability distributions are illustrated in Figure 6-5.

In the illustration of Figure 6-5, the triangular distribution function *RiskTriangular(2,3,6)* would specify that a variable in the model could take a minimum value of 2, a most likely value of 3 and a maximum value of 6. Simulation is then used to generate a distribution of possible outcomes for each possible trial solution that is generated by the optimiser. Similarly, the uniform distribution function *RiskUniform(2, 6)* would mean that the model could assume a minimum value of 2, a maximum value of 6, and that any value from 2 to 6 has equal chance of occurring. More so, the normal distribution function *RiskNormal(4, 2)* would specify that the model could take a mean value (μ) as 4 and standard deviation (σ) as 2.

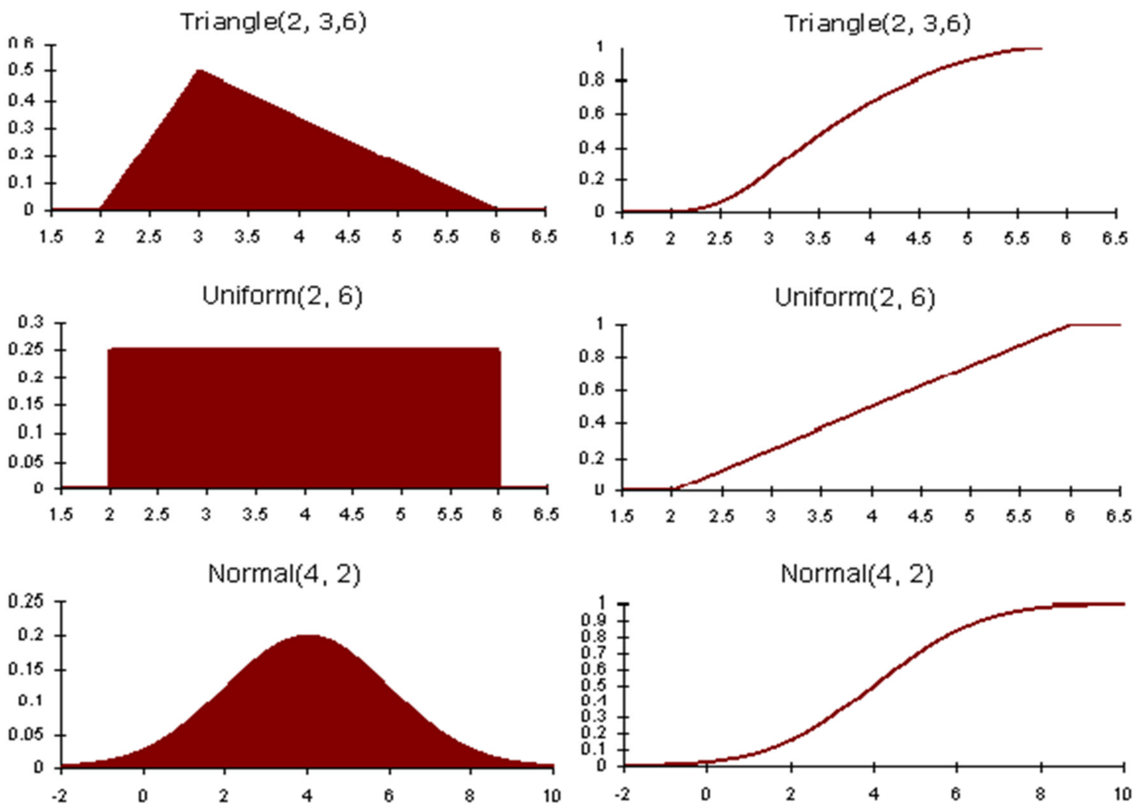


Figure 6-5 Triangular,uniform, and normal cumulative probability distributions (Source: Vose software)

6.5.5 Sensitivity analysis

Sensitivity analysis is used to identify significant inputs by estimating the consequences of limited changes in the value of these inputs. It helps a decision-maker to identify the variables that have major effect on the output and that would need more attention and investigation. For instance in an economic evaluation of an investment project, like determining NPV of the project, one or more input cost variables are changed independently or collectively within reasonable limits to observe the probable impact of the change on the NPV and its likely IRR and payback period. Alternatively the aim may be to estimate the change in one variable like grid electricity price that would reduce the NPV to zero. This would show the value of grid electricity price below or above which it is not worthwhile investing in the project (Khatip, 2014; Palisade Corporation, 2013).

Another aim of sensitivity analysis may be **break-even analysis**, to estimate the values of inputs and outputs that would make the benefits of the project fall below the cut-off rate. Cut-off rate is a rate predetermined as a threshold below which projects should not be accepted. Sensitivity analysis is carried out with three different analytical techniques, namely, change in output statistic, regression analysis, and rank correlation. The results of sensitivity analysis can be displayed as a "tornado" type chart as illustrated in Figure 6-6, having longer bars at the top representing the most significant input variables.

The double-sided tornado chart shows the positive and negative impact on actual output values (information very valuable to decision-makers, and more easier to understand than statistical coefficients).

The results can also be presented as "spider plots" as illustrated in Figure 6-7 . This graph display the change in mean output across the range of values for all the various inputs. It gives a very intuitive view on sensitivity analysis.

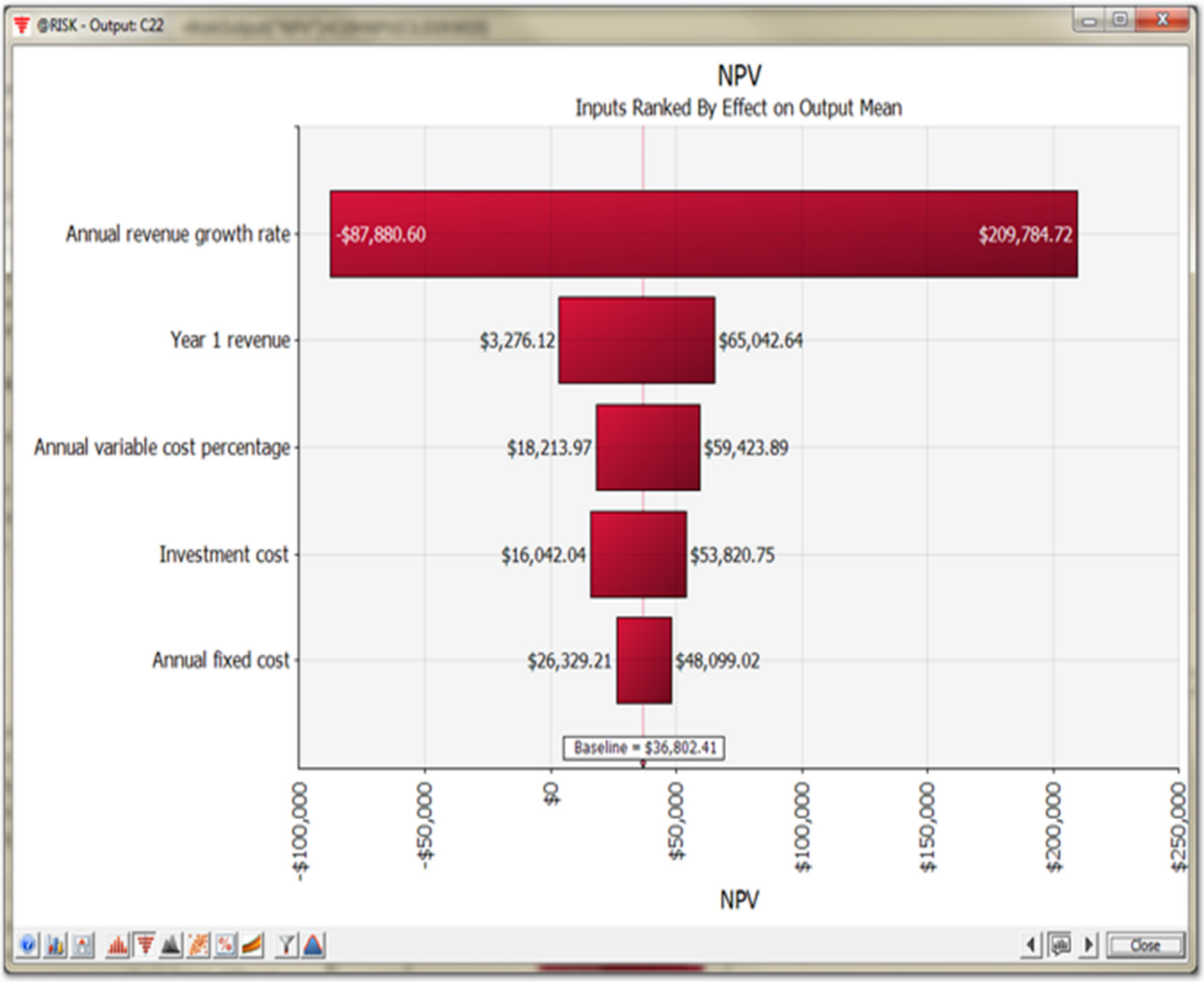


Figure 6-6 Tornado chart showing sensitivity results (Source: Palisade Corporation, 2014)

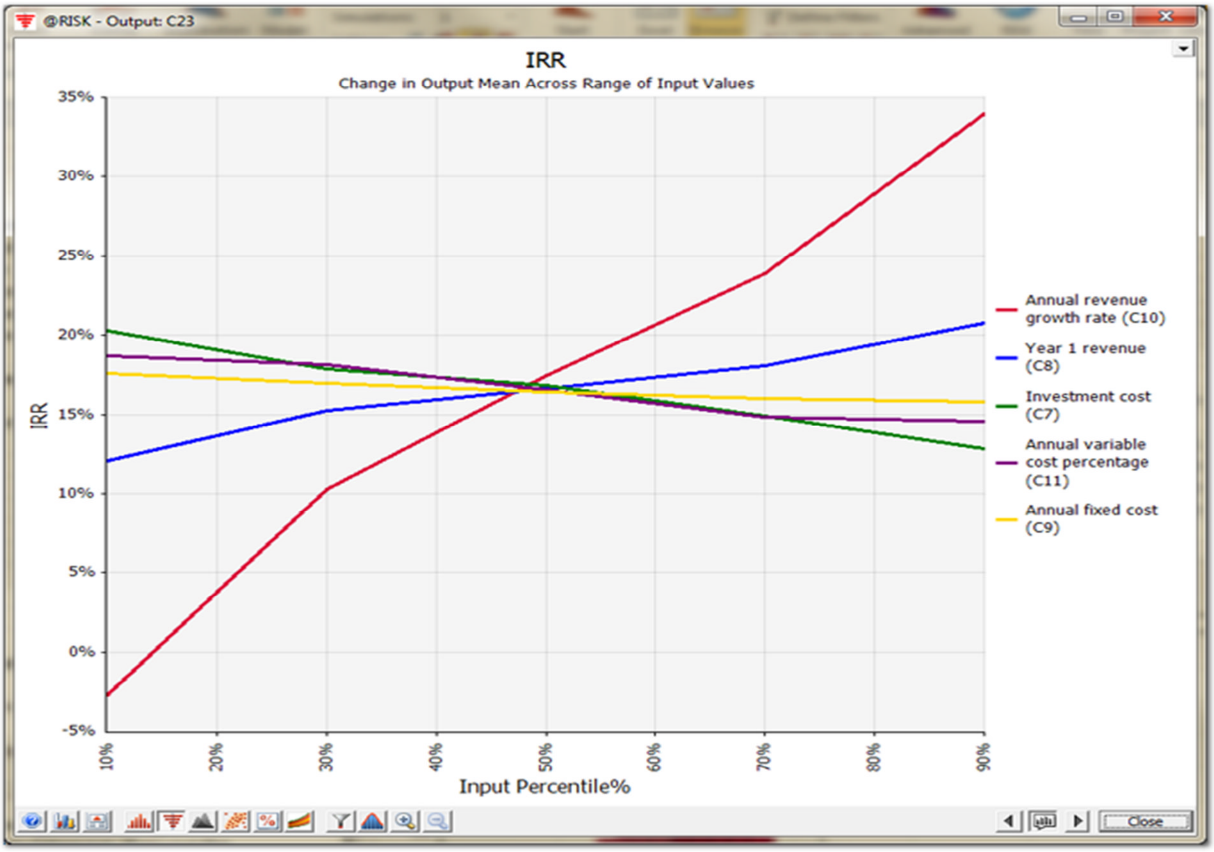


Figure 6-7 Sensitivity analysis results on spider plot (Source: Palisade Corporation, 2014)

6.6 Chapter summary

The key imports of this chapter are outlined below.

- TERA methodology is outlined.
- The various modules that make up TERA framework for ADIGT-CHP are highlighted, namely, engine performance, emissions, economic, and risk, modules.
- The economic module is examined in detail having its components x-rayed.
- The criteria for assessing economic viability of ADIGT-CHP are defined which include SPBP, NPV, and IRR.
- The algorithm for the economic evaluation model developed in this research is thoroughly laid out.
- Cost elements of the economic evaluation model are defined which include capital/installation cost, energy cost (costs of fuel, electricity, and steam), operation and maintenance cost (fixed and variable), emission cost, cost escalation rate, loan repayment, interest on loan, and market discount rate.

7 TERA IMPLEMENTATION FOR ADIGT-CHP IN THE PETROCHEMICAL INDUSTRY: CASE STUDIES

7.1 Overview

The development of the economic evaluation module of TERA for ADIGT-CHP in the petrochemical industry is accomplished by considering typical case studies and following the methodology outlined in chapter 6. The algorithm of the economic model discussed in chapter 6 is herein implemented using two case studies, one for LS-ADIGT-CHP, and the other for SS-ADIGT-CHP. In this regard, two inspiring petrochemical/refinery CHP sites in the United Kingdom are identified for the case studies, one for each category of the LS- and SS-ADIGT-CHP respectively. In each case, the model is deployed to evaluate the techno-economic viability of both the simple cycle and advanced cycle engines ADIGT-CHP against the conventional case of purchasing power from grid and producing steam in on-site boiler.

In doing so, the model computes NPV, IRR, and SPBP for each engine cycle ADIGT-CHP configuration and compares the results in their different categories of large-scale and small-scale ADIGT-CHP respectively. More so, the risk evaluation software @Risk 6.0 of Palisade Corporation is integrated with the model as add-in to conduct risk and sensitivity analysis of mean NPV with respect to variations in some inputs. The software @Risk 6.0 applies a modified Monte Carlo sampling method known as Latin Hypercube sampling technique to carry out risk analysis simulation iterations. This Latin Hypercube sampling technique was discussed in section 6.5.3 .

It is important to note that in both case studies, the CHP steam flow requirements are meant for process and room heating in the plant complexes. Nevertheless, the steam flow is analysed as single bulk in each case not accounting for different end uses. Similarly, the CHP power requirements in both case studies are meant to serve various purposes, namely lighting, electrical/electronic appliances, electrical machines and drives, etc, but the power is analysed as single bulk in each case, not accounting for various end uses.

7.2 Case study 1: large-scale ADIGT-CHP

One of the case studies is a Large-scale Refinery and Chemical plant CHP (LSRCP-CHP) in the United Kingdom inspired by Ineos Refinery and Chemicals CHP. The LSRCP-CHP has an installed capacity of 295MW of power, and 2 x 250 tonnes/hour of steam (Greenpeace, 2008). This gives a total of

500tonnes/hour of steam = 47.61 x 500 = 23804.51kW$_{th}$ (because 1tonne/hour of steam = 47.61kW$_{th}$).

7.2.1 ADIGT-CHP power plant performance module for LSRCP

With the nominal capacity energy demand of the LSRCP stated in section 7.2, 3 x 100MW ADIGTs and an additional 1 x 43.85MW ADIGT-CHP of same 50Hz frequency are considered to supply the demanded power and steam. This arrangement is made knowing that during hot days (in the summer) power generation on site may fall below demanded power. There may be surplus power and steam generated on site which are exported to the Grid. Conversely during plant outages power is imported from the Grid and steam produced in a stand-by boiler. The DP performance evaluation of the 100MW ADIGT engine cycles using TURBOMATCH were shown in Table 4-4 while those of the 43.85MW ADIGT-CHP cycles were shown in Table 5-2. Similarly, verification of the engines models were presented in Table 4-5 and Table 4-3 respectively.

7.2.2 ADIGT-CHP engines emissions module for LSRCP

HEPHAESTUS code is employed to estimate the engines emission indices utilising dry low NO_x technology (DLN), and DP results were presented in Table 4-7 and Table 4-8. The total annual emissions of the ADIGT cycles are computed based on the annual fuel consumptions, and the results are stated in Table 7-4, Table 7-6, and Table 7-8.

7.2.3 Economic analysis of LSRCP CHP

To determine the economic viability of the LSRCP ADIGT-CHP its profitability is measured against the conventional case of purchasing power from the Grid and employing a boiler to generate steam. The method of economic evaluation discussed in chapter 6 is applied which include the criteria of NPV, SPBP, and IRR, to compare investment in both simple (SC) and advanced cycle (IC and ICR) LS-ADIGT-CHP with respect to conventional case. In the analysis 2013 rate of Great Britain Pound (£) is used against United State Dollar ($).

The conventional case of purchasing grid power and producing steam in on-site boiler is firstly analysed followed by the analyses of SC, IC, and ICR LS-ADIGT-CHP cycles. Then the viabilities of the LS-ADIGT-CHP cycle options over the conventional case are compared.

7.2.3.1 Conventional case (grid power and on-site boiler) of LSRCP

7.2.3.1.1 Energy demand of LSRCP

The annual power and steam demand of the LSRCP are computed based on the installed capacity stated in section 7.2 and are shown in Table 7-1 below. It is assumed that the refinery and chemical plant operates throughout the year.

Table 7-1 annual energy demand of LSRCP

Season	Days	Power consumption demand (kWhe)	Steam consumption demand (kWh_{th})
Winter	37 Hot days	279660000	22566675
	56 Cold days	384090000	30993472
Spring	39 Hot days	293820000	23709292
	51 Cold days	354590000	28613021
Summer	46 Hot days	284675000	22971352
	48 Cold days	348985000	28160735
Autumn	36 Hot days	255765000	20638510
	52 Cold days	382615000	30874449
Annual Total	365 days	2584200000	208527508

Assumptions: the following are assumed in addition to those stated in section 6.4.2.1

- The Refining and Chemical plant operate throughout the year implying 8760 hours of power purchase from grid and on-site steam generation in boiler.
- Two industrial boilers of 23.804MW_{th} capacity each are installed on site of which one would be kept on stand-by.
- Year (0) is taken as initial installation and site construction period so that operation on site commences in year (1).
- Investment capital is made of Loan

The capital cost and annual operation cost are computed as shown in Appendix D.1 . The boiler capital cost is obtained as £3,808,722, while year (1) annual operation cost is found to be £269,263,430. The present value of year (1) annual operation cost is computed as £244,784,937. Loan is taken as £273,072,152, made of the sum of boiler capital cost and year (1) annual operation cost, whereas equal annual loan repayment is calculated as £35,364,093 (see Appendix D.1). Two years loan holiday is allowed so that annual loan repayment would commence in year (3).

7.2.3.2 Conventional case life-cycle cash flow of LSRCP

Applying the escalation rates of prices (costs) to the life-cycle as spelled out in section 6.4.2.1, the life-cycle cash flow of the conventional case is computed and result is shown in Table 7-2.

Table 7-2 **Conventional case economic analysis of LSRCP (Grid electricity plus Boiler)**

			Electricity price £/kWh :		**0.1**	**interest rate(%):**	**5**
Boiler O & M cost £/kWh:		**0.004**	**Grid electricity /annum kWh:**		**2584200000**	**Loan duration(yrs):**	**10**
Boiler capital cost £/kW:		**80**	**Hours of operation/annum:**		**8760**	**Loan (£):**	**273072152.00**
Boiler capital cost £:		**3808721.6**	**Boiler gas fuel price £/kWh:**		**0.05**	**Repayment Holiday:**	**2 yrs**
emissions tax £ /kWh :		**0.002**	**10% Discount rate (d) :**		**0.1**		
End of year (t)	Boiler O & M cost, -$C_{Bo/m}$ (3% escalation rate) (£)	Grid electricity cost, -C_{Ge} (5% escalation rate) (£)	Boiler fuel cost, -C_{Bh} (5% escalation rate)(£)	Boiler emission cost - C_{Bemtx} (3% escalation rate) (£)	Annual Loan repayment, C_{Lr} (£)	Annual cost (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	834110	258420000	10426375	417055	0	269263430	244784937
2	859133	271341000	10947694	429567	0	282718261	233651455
3	884907	284908050	11495079	442454	35364093	332209676	249594046
4	911455	299153453	12069833	455727	35364093	347043106	237035111
5	938798	314111125	12673324	469399	35364093	362617942	225157212
6	966962	329816681	13306991	483481	35364093	378971246	213919389
7	995971	346307515	13972340	497985	35364093	396141934	203283449
8	1025850	363622891	14670957	512925	35364093	414170866	193213766
9	1056626	381804036	15404505	528313	35364093	433100947	183677080
10	1088324	400894238	16174730	544162	35364093	452977223	174642329
11	1120974	420938949	16983467	560487	35364093	473846996	166080482
12	1154603	441985897	17832640	577302	35364093	495759932	157964392
13	1189241	464085192	18724272	594621	0	483404085	140024944
14	1224919	487289451	19660486	612459	0	507562397	133657043
15	1261666	511653924	20643510	630833	0	532928267	127578790
16	1299516	537236620	21675686	649758	0	559562064	121777008
17	1338502	564098451	22759470	669251	0	587527172	116239119
18	1378657	592303374	23897443	689328	0	616890145	110953115
19	1420016	621918542	25092316	710008	0	647720866	105907537
20	1462617	653014469	26346931	731308	0	680092709	101091448
∑	**22412849**	**8544903859**	**344758050**	**11206424**	**353640930**	**9254509263**	**3440232652**

7.2.3.3 LSRCP ADIGT-CHP cases

The CHP economic analysis is implemented for both the simple and advanced cycle LS-ADIGT-CHP, and results compared. The set of power plant is as described in section 7.2.1. In conjunction with the assumptions stated in sections 6.4.2.1 and 7.2.3.1, it is assumed that one industrial boiler of 23.804MW_{th} capacity is installed on site which would be kept on stand-by and brought on stream during CHP outages.

7.2.3.3.1 Simple cycle (SC) LS- ADIGT-CHP case for LSRCP

7.2.3.3.1.1 Energy generation and consumption for SC LS-ADIGT-CHP of LSRCP

The annual power and steam demand of the LSRCP were shown in Table 7-1. However, the three ADIGT-CHP cycle configurations generate different amounts of power and steam based on their respective features and prevailing climatic conditions of the site. The energy generation of the SC LS-ADIGT-CHP cycle is computed and is presented in Table 7-3. It is assumed that the power plant has an availability of about 95%.

Initial cash flow is the sum of installation costs of three 100MWe ADIGTs, one 43.85MWe ADIGT (with a set of HRSG), and one 23.805MW_{th} boiler. The capital cost and annual cash flow are computed as shown in Appendix D.2 . The installation/capital cost is obtained as £242,599,361, while year (1) annual net cash flow is found to be £41,857,125. The present value of year (1) annual net cash flow is computed to be £38,051,932. Loan is taken as £242,599,361, made of capital cost, whereas equal annual loan repayment is calculated to be £31,417,727 (see Appendix D.2). Two years loan holiday is allowed so that annual loan repayment would commence in year (3).

7.2.3.3.1.2 Simple cycle LS-ADIGT-CHP case life cycle cash flow for LSRCP:

Applying the escalation rates of prices (costs) to the life-cycle as spelled out in section 6.4.2.1, the life-cycle cash flow of the simple cycle CHP case is computed and result is shown in Table 7-4 . Equal annual loan repayment commences in year (3).

Simple-payback-period (SPBP) is calculated as shown in Appendix D.2.1, and it is found to be 4.8 years. Similarly, NPV is calculated as shown in Appendix D.2.2 , and obtained as £241,192,965. More so, by method of iteration using Equation 6-7 the internal rate of return, IRR for the SC LS-ADIGT-CHP case is determined to be 18.8%.

Table 7-3 Energy generation and consumption for SC LS-ADIGT-CHP of LSRCP

Season	Days of power plant on stream	Average daily temp. (^oC)	Power consumption demand from power plant (kWh_e)	Power generated from 3 x 100MW GT (kWh_e)	Power generation compensation from 1 x 43MW GT	Total Power generated (kWh_e)	Excess power exported to grid (kWh_e)	Grid electricity during plant outages (kWh_e)	Heat consumption demand from CHP (kWh_{th})	Heat generated from 43MW CHP (kWh_{th})	Excess heat exported (kWh_{th})	Boiler heat during CHP outages (kWh_{th})
Winter	37 Warm days	6	268450000	288500940	39266455	327767394.50	59317395	11210000	21662104	42330353	20668249	904571
	54 Cold days	0	375240000	425670984	56305398	481976382.00	106736382	8850000	30279337	59315042	29035705	714135
Spring	37 Hot days	10	275235000	280343642	39199715	319543356.60	44308357	18585000	22209608	43245449	21035841	1499684
	49 Cold days	2	339840000	385513344	50993568	436506912.00	96666912	14750000	27422796	53719283	26296487	1190226
Summer	39 Hot days	20	262550000	235465832	34973262	270439093.50	7889094	22125000	21186014	40962021	19776007	1785338
	46 Cold days	10	328925000	335030183	46846391	381876573.00	52951573	20060000	26542029	51681324	25139295	1618707
Autumn	34 Hot days	13	239835000	244286582	34157951	278444532.60	38609533	15930000	19353067	37683333	18330266	1285444
	51 Cold days	6	364915000	392171058	53376488	445547546.15	80632546	17700000	29446179	57541370	28095191	1428271
Annual	Total		2454990000	2586982563	355119227	2942101790	487111790	129210000	198101132	386478173	188377041	10426375

Table 7-4 Simple cycle (SC) LS-ADIGT-CHP case economic analysis of LSRCP

				Boiler O&M cost £/kWh :	0.004		
10% Discount rate (d) :	0.1	GT gas fuel price (£/kWh) :	0.05	Electricity tariff from grid £/kWh :	0.1	interest rate(%):	5
CHP capital cost £/kW:	700	GT fuel consumed/annum (kg) :	532066404.2	Electricity consumed/annum (kWh) :	2454990000	Loan duration(yrs):	10
CHP O&M var cost £/kWh:	0.02	Hours of CHP outages/annum:	438	Grid electricity /annum (kWh) :	129210000	Loan (£):	242599361
Initial cash flow (F_0) £:	242599361	Hours of CHP operation/annum:	8322	Boiler gas fuel price £/kWh :	0.05	Repayment Holiday	2 yrs
	Excess electricity sold to Grid/annum(kWh):		487111790	Steam export price £/kWh :	0.025		
GT emission tax £/kg :	0.005	Boiler capital cost £/kW :	80	Electricity export tariff to grid £/kWh :	0.05		
Boiler emission cost £:	5025.512933	GT emission/annum kg:	2745391763	CHP Fixed O&M cost £:	1719250		

End of year (t)	O & M cost, $-C_{o/m}$ (3% escalation rate) (£)	GT fuel cost, $-C_f$ (5% escalation rate) (£)	Grid electricity cost, $-C_{Ge}$ (5% escalation rate) during outages of CHP (£)	Boiler heat cost, $-C_{Bh}$ (5% escalation rate) during outages of CHP (£)	Emission tax, $-C_{emtx}$ (3% escalation rate)(£)	Saved electricity cost , $+C_e$ (5% escalation rate) (£)	Saved heat cost , $+C_h$ (5% escalation rate) (£)	Revenue on excess electricity sold to Grid, $+R_e$ (5% escalation rate) (£)	Revenue on excess heat sold, $+R_h$ (5% escalation rate)(£)	Annual Loan repayment, C_{LR} (£)	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	68332555	147105090	12921000	521319	13731984	245499000	9905057	24355590	4709426	0	41857125	38051932
2	70382531	154460344	13567050	547385	14143944	257773950	10400309	25573369	4944897	0	45591272	37678737
3	72494007	162183361	14245403	574754	14568262	270662648	10920325	26852037	5192142	31417727	18143638	13631584
4	74668828	170292529	14957673	603492	15005310	284195780	11466341	28194639	5451749	31417727	22362951	15274197
5	76908892	178807156	15705556	633666	15455469	298405569	12039658	29604371	5724337	31417727	26845468	16668924
6	79216159	187747514	16490834	665350	15919133	313325847	12641641	31084590	6010554	31417727	31605915	17840715
7	81592644	197134889	17315376	698617	16396707	328992140	13273723	32638819	6311081	31417727	36659803	18812276
8	84040423	206991634	18181145	733548	16888609	345441747	13937409	34270760	6626635	31417727	42023467	19604257
9	86561636	217341215	19090202	770225	17395267	362713834	14634280	35984298	6957967	31417727	47714107	20235439
10	89158485	228208276	20044712	808737	17917125	380849526	15365994	37783513	7305865	31417727	53749837	20722889
11	91833240	239618690	21046947	849173	18454639	399892002	16134293	39672689	7671159	31417727	60149727	21082112
12	94588237	251599624	22099295	891632	19008278	419886602	16941008	41656323	8054717	31417727	66933857	21327190
13	97425884	264179606	23204260	936214	19578526	440880932	17788059	43739140	8457453	0	105541094	30571496
14	100348660	277388586	24364473	983024	20165882	462924979	18677462	45926096	8880325	0	113158237	29798100
15	103359120	291258015	25582696	1032176	20770858	486071228	19611335	48222401	9324341	0	121226440	29020646
16	106459894	305820916	26861831	1083784	21393984	510374789	20591901	50633521	9790558	0	129770361	28241812
17	109653691	321111962	28204923	1137973	22035804	535893529	21621496	53165197	10280086	0	138815957	27463997
18	112943301	337167560	29615169	1194872	22696878	562688205	22702571	55823457	10794091	0	148390544	26689344
19	116331600	354025938	31095927	1254616	23377784	590822615	23837700	58614630	11333795	0	158522875	25919757
20	119821548	371727235	32650723	1317347	24079118	620363746	25029585	61545362	11900485	0	169243207	25156924
∑	**1836121337**	**4864170138**	**427245193**	**17237902**	**368983561**	**8117658666**	**327520147**	**805340805**	**155721665**	**314177271**	**1578305881**	**483792326**
Annual running cost of CHP (£) =					**213546932**							
Present value of annual running cost of CHP (£) =					**194133574**				**NPV_{CHP} =**	**241192965**		
Saving in CHP running cost over conventional running cost (£)=					**50651362**				**IRR =**	**0.183**	**for NPV =**	**0.00**
Simple payback period SPBP =					**4.8**	**Years**						

7.2.3.3.2 Intercooled cycle (IC) LS-ADIGT-CHP case for LSRCP

7.2.3.3.2.1 Energy generation and consumption for IC LS-ADIGT-CHP of LSRCP

Following same assumption in section 7.2.3.3.1.1 , the energy generation of the IC LS-ADIGT-CHP cycle is computed and is shown in Table 7-5.

Assuming 0.7% increment in GT capital cost due to intercooler, and applying the same method of Appendix D.2 as stated in section 7.2.3.3.1.1, the installation/capital cost for IC cycle ADIGT-CHP is calculated to be £244,318,611, which is equal to the loan taken.

7.2.3.3.2.2 Year 1 annual net cash flow for IC LS-ADIGT-CHP case of LSRCP:

Using the same method of Appendix D.2

$C_{o/m} = £63,277,557$; $\mathrm{C_f} = £139,711,279$; $\mathrm{C_{Ge}} = £12,921,000$;
$\mathrm{C_{Bh}} = £521,319$; $\mathrm{C_{emtx}} = £13,201,004$; $\mathrm{C_e} = £245,499,000$

$\mathrm{C_h} = £9,905,057$; $\mathrm{R_e} = £16,961,779$; $\mathrm{R_h} = £1,657,772$
$\text{Year 1 annual net cash flow}, \mathrm{F_1} = £44,391,448$

$\text{Present value of year 1 annual net cash flow} = £40,355,862$, and equal annual loan repayment $\mathrm{C_{Lr}} = £31,640,378$

7.2.3.3.2.3 IC LS-ADIGT-CHP case life cycle cash flow for LSRCP:

Applying the escalation rates of prices (costs) to the life-cycle as spelled out in section 6.4.2.1, the life-cycle cash flow of the IC ADIGT-CHP case is computed and result is shown in Table 7-6 .

As shown in Appendix D.2.3, simple-payback-period (SPBP) is calculated to be 4.6 years. Similarly, by the method presented in Appendix D.2.4, NPV is obtained to be £259,757,273. Besides, by method of iteration using Equation 6-7 the internal rate of return (IRR) for the IC LS-ADIGT-CHP case is determined to be 19%.

Table 7-5 Energy generation and consumption for IC LS-ADIGT-CHP of LSRCP

Season	Days of power plant on stream	Average daily temp. (^{o}C)	Power consumption demand from power plant (kWh_e)	Power generated from 3 x 100MW GT (kWh_e)	Power generation compensation from 1 x 43MW GT (kWh_e)	Total Power generated (kWh_e)	Excess power exported to grid (kWh_e)	Grid electricity during plant outages (kWh_e)	Heat consumption demand from CHP (kWh_{th})	Heat generated from 43MW CHP (kWh_{th})	Excess heat exported (kWh_{th})	Boiler heat during CHP outages (kWh_{th})
Winter	37 Warm days	6	268450000	269775870	38082954	307858824.00	39408824	11210000	21662104	28916536	7254432	904571
	54 Cold days	0	375240000	384379956	53379862	437759817.60	62519818	8850000	30279337	40450762	10171425	714135
Spring	37 Hot days	10	275235000	270797652	38938242	309735893.85	34500894	18585000	22209608	29626845	7417238	1499684
	49 Cold days	2	339840000	348117696	48344026	396461721.60	56621722	14750000	27422796	36634653	9211857	1190226
Summer	39 Hot days	20	262550000	246948567	36921294	283869861.00	21319861	22125000	21186014	28253313	7067299	1785338
	46 Cold days	10	328925000	323622060	46533912	370155971.75	41230972	20060000	26542029	35406144	8864116	1618707
Autumn	34 Hot days	13	239835000	235968372	33930108	269898479.85	30063480	15930000	19353067	25816319	6463252	1285444
	51 Cold days	6	364915000	366717309	51767708	418485016.80	53570017	17700000	29446179	39307423	9861245	1428271
Annual	Total		2454990000	2446327482	347898104	2794225586	339235586	129210000	198101132	264411996	66310863	10426375

Table 7-6 Intercooled cycle (IC) LS-ADIGT-CHP case economic analysis of LSRCP

				Boiler O&M cost £/kWh:	0.004		
10% Discount rate (d) :	0.1	GT gas fuel price (£/kg):	0.05	Electricity tariff £/kWh:	0.1	interest rate(%):	5
CHP capital cost £/kW :	705	GT fuel consumed/annum (kg):	519228887	GT power consumed/annum (kWh):	2454990000	Loan duration(yrs):	10
CHP O&M var cost £/kWh:	0.02	Hours of CHP outages/annum:	438	Grid electricity /annum (kWh):	129210000	Loan (£):	244318610.80
Initial cash flow (F_0) £:	244318610.8	Hours of CHP operation/annum:	8322	Boiler gas oil price £/kWh:	0.05	Repayment Holiday:	2 yrs
	Excess electricity sold to Grid/annum(kWh):		339235586	Steam export price £/kWh:	0.025		
GT emission tax £/kg :	0.005	Boiler capital cost £/kW :	80	Electricity export tariff to grid £/kWh:	0.05		
Boiler emission cost £:	5025.512933	GT emission/annum kg:	2639195705	CHP Fixed O&M cost £:	2063100		

End of year (t)	O & M cost, $-C_{o/m}$ (3% escalation rate) (£)	GT fuel cost, $-C_f$ (5% escalation rate) (£)	Grid electricity cost, $-C_{Ge}$ (5% escalation rate) during outages of CHP (£)	Boiler heat cost, $-C_{Bh}$ (5% escalation rate) during outages of CHP (£)	Emission tax, $-C_{emtx}$ (3% escalation rate)(£)	Saved electricity cost, $+C_e$ (5% escalation rate) (£)	Saved heat cost, $+C_h$ (5% escalation rate) (£)	Revenue on excess electricity sold to Grid, $+R_e$ (5% escalation rate) (£)	Revenue on excess heat sold, $+R_h$ (5% escalation rate)(£)	Annual Loan repayment, CLr (£)	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	63277557	139711279	12921000	521319	13201004	245499000	9905057	16961779	1657772	0	44391448	40355862
2	65175884	146696843	13567050	547385	13597034	257773950	10400309	17809868	1740660	0	48140592	39785613
3	67131160	154031685	14245403	574754	14004945	270662648	10920325	18700362	1827693	31640378	20482702	15388957
4	69145095	161733270	14957673	603492	14425094	284195780	11466341	19635380	1919078	31640378	24711578	16878340
5	71219448	169819933	15705556	633666	14857846	298405569	12039658	20617149	2015032	31640378	29200580	18131263
6	73356031	178310930	16490834	665350	15303582	313325847	12641641	21648006	2115783	31640378	33964173	19171890
7	75556712	187226476	17315376	698617	15762689	328992140	13273723	22730407	2221572	31640378	39017593	20022195
8	77823414	196587800	18181145	733548	16235570	345441747	13937409	23866927	2332651	31640378	44376880	20702142
9	80158116	206417190	19090202	770225	16722637	362713834	14634280	25060273	2449284	31640378	50058922	21229870
10	82562860	216738050	20044712	808737	17224316	380849526	15365994	26313287	2571748	31640378	56081502	21621847
11	85039745	227574952	21046947	849173	17741046	399892002	16134293	27628951	2700335	31640378	62463340	21893020
12	87590938	238953700	22099295	891632	18273277	419886602	16941008	29010399	2835352	31640378	69224142	22056945
13	90218666	250901385	23204260	936214	18821475	440880932	17788059	30460919	2977120	0	108025030	31291003
14	92925226	263446454	24364473	983024	19386119	462924979	18677462	31983965	3125976	0	115607084	30442958
15	95712983	276618777	25582696	1032176	19967703	486071228	19611335	33583163	3282274	0	123633665	29596917
16	98584372	290449716	26861831	1083784	20566734	510374789	20591901	35262321	3446388	0	132128962	28755112
17	101541903	304972201	28204923	1137973	21183736	535893529	21621496	37025437	3618707	0	141118432	27919530
18	104588160	320220811	29615169	1194872	21819248	562688205	22702571	38876709	3799643	0	150628867	27091926
19	107725805	336231852	31095927	1254616	22473826	590822615	23837700	40820544	3989625	0	160688458	26273847
20	110957579	353043445	32650723	1317347	23148040	620363746	25029585	42861572	4189106	0	171326874	25466648
Σ	**1700291657**	**4619686750**	**427245193**	**17237902**	**354715922**	**8117658666**	**327520147**	**560857417**	**54815799**	**316403778**	**1625270826**	**504075884**

Annual running cost of CHP	**=**	**211012608**				
Present value of annual running cost of CHP (£)	**=**	**191829644**	**NPV =**	**259757273**		
Saving in CHP running cost over conventional running cost=		**52955293**	**IRR =**	**0.190**	**for NPV =**	**0.00**
Simple payback period SPBP	**=**	**4.6**	**Years**			

7.2.3.3.3 Intercooled/recuperated cycle ICR LS-ADIGT-CHP case for LSRCP

7.2.3.3.3.1 Energy generation and consumption for ICR LS-ADIGT-CHP of LSRCP

Following same assumption in section 7.2.3.3.1.1, the energy generation of the IC LS-ADIGT-CHP cycle is computed and is presented in Table 7-7.

Assuming 1.4% increment in GT capital cost due to intercooler and recuperator, and applying the same method of Appendix D.2 as stated in section 7.2.3.3.1.1, the installation/capital cost for IC cycle ADIGT-CHP is calculated to be £246,037,861, which is equal to the loan taken

7.2.3.3.3.2 Year 1 annual net cash flow for ICR LS-ADIGT-CHP case of LSRCP:

Applying the same method of Appendix D.2

$C_{o/m} = £63,862,251$; $\mathrm{C_f} = £139,763,031$; $\mathrm{C_{Ge}} = £12,921,000$; $\mathrm{C_{bh}} = £521,319$; $\mathrm{C_{emtx}} = £13,403,291$; $\mathrm{C_e} = £245,499,000$

$\mathrm{C_h} = £9,905,057$, $\mathrm{R_e} = £17,013,531$; $\mathrm{R_h} = £1,932,950$
Year 1 annual net cash flow, $\mathrm{F_1} = £43,879,646$

Present value of year 1 annual net cash flow $= £39,890,587$, and equal annual loan repayment $\mathrm{C_{Lr}} = £31,863,029$

7.2.3.3.3.3 ICR LS-ADIGT-CHP case life cycle cash flow for LSRCP:

Applying the escalation rates of prices (costs) to the life-cycle as stated in section 6.4.2.1, the life-cycle cash flow of the ICR ADIGT-CHP case is computed and result is shown in Table 7-8 .

Simple-payback-period (SPBP) was calculated as shown in Appendix D.2.5, and it is found to be 4.7 years. Similarly, NPV was calculated as shown in Appendix D.2.6 , and obtained as £252,016,032. More so, by method of iteration using Equation 6-7 the IRR for the ICR LS-ADIGT-CHP case is determined to be 18.7%.

Figure 7-1, Figure 7-2, and Figure 7-3 show the comparison between the NPV, SPBP, and IRR respectively of the simple, intercooled, and ICR cycle ADIGT-CHP for the LSRCP. The percentage savings in operational cost of the three LSRCP-CHP scenarios over the conventional case is presented in Figure 7-4.

Table 7-7 Energy generation and consumption for ICR LS-ADIGT-CHP of LSRCP

Season	Days of power plant on stream	Average daily temp. (^oC)	Power consumption demand from power plant (kWh_e)	Power generated from 3 x 100MW GT (kWh_e)	Power generation compensation from 1 x 43MW GT (kWh_e)	Total Power generated (kWh_e)	Excess power exported to grid (kWh_e)	Grid electricity during plant outages (kWh_e)	Heat consumption demand from CHP (kWh_{th})	Heat generated from 43MW CHP (kWh_{th})	Excess heat exported (kWh_{th})	Boiler heat during CHP outages (kWh_{th})
Winter	37 Warm days	6	268450000	269490585	38089006	307579590.50	39129590	11210000	21662104	30121828	8459724	904571
	54 Cold days	0	375240000	384597468	53389529	437986996.80	62746997	8850000	30279337	42147320	11867983	714135
Spring	37 Hot days	10	275235000	271116738	38942674	310059411.60	34824412	18585000	22209608	30855901	8646293	1499684
	49 Cold days	2	339840000	348314688	48352781	396667468.80	56827469	14750000	27422796	38171157	10748362	1190226
Summer	39 Hot days	20	262550000	247197144	36941586	284138730.00	21588730	22125000	21186014	29414845	8228831	1785338
	46 Cold days	10	328925000	324003390	46539208	370542598.00	41617598	20060000	26542029	36874951	10332923	1618707
Autumn	34 Hot days	13	239835000	236246418	33933970	270180387.60	30345388	15930000	19353067	26887296	7534230	1285444
	51 Cold days	6	364915000	366329510	51775934	418105443.35	53190443	17700000	29446179	40945825	11499646	1428271
Annual	Total		2454990000	2447295941	347964686	2795260627	340270627	129210000	198101132	275419123	77317991	10426375

Table 7-8 **Intercooled-recuperated cycle (ICR) LS-ADIGT-CHP case economic analysis of LSRCP**

				Boiler O&M cost £/kWh:	0.004		
10% Discount rate (d):	0.1	GT gas fuel price (£/kWh) :	0.05	Electricity tariff £/kWh:	0.1	interest rate(%):	5
GT capital cost £/kW :	710	GT fuel consumed/annum (kg) :	525718049.8	GT power consumed/annum (kWh):	2454990000	Loan duration(yrs):	10
GT-CHP O&M var cost £/kWh:	0.02	Hours of CHP outages/annum:	438	Grid electricity /annum (kWh):	129210000	Loan (£):	246037860.80
Initial cash flow (F_o) £:	246037860.8	Hours of CHP operation/annum:	8322	Boiler gas oil price £/kWh:	0.05	Repayment Holida	2 yrs
		Excess electricity sold to Grid/annum(kWh):	340270627	Steam export price £/kWh:	0.025		
GT emission tax £/kg :	0.005	Boiler capital cost £/kW :	80	Electricity export tariff to grid £/kWh:	0.05		
Boiler emission cost £:	5025.512933	GT emission/annum kg:	2679653138	GT-CHP Fixed O&M cost £:	2406950		

End of year (t)	O & M cost, $-C_{o/m}$ (3% escalation rate) (£)	GT fuel cost, $-C_f$ (5% escalation rate) (£)	Grid electricity cost, $-C_{Ge}$ (5% escalation rate) during outages of CHP (£)	Boiler heat cost, $-C_{Bh}$ (5% escalation rate) during outages of CHP (£)	Emission tax, $-C_{emtx}$ (3% escalation rate)(£)	Saved electricity cost , $+C_e$ (5% escalation rate) (£)	Saved heat cost , $+C_h$ (5% escalation rate) (£)	Revenue on excess electricity sold to Grid, $+R_e$ (5% escalation rate) (£)	Revenue on excess heat sold, $+R_h$ (5% escalation rate)(£)	Annual Loan repayment, CLr (£)	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	63862250.49	139763031	12921000	521319	13403291	245499000	9905057	17013531	1932950	0	43879646	39890587
2	65778118.00	146751183	13567050	547385	13805390	257773950	10400309	17864208	2029597	0	47618939	39354495
3	67751461.54	154088742	14245403	574754	14219552	270662648	10920325	18757418	2131077	31863029	19728528	14822335
4	69784005.39	161793179	14957673	603492	14646138	284195780	11466341	19695289	2237631	31863029	23947526	16356482
5	71877525.55	169882838	15705556	633666	15085522	298405569	12039658	20680054	2349513	31863029	28426656	17650717
6	74033851.32	178376980	16490834	665350	15538088	313325847	12641641	21714056	2466988	31863029	33180401	18729472
7	76254866.86	187295829	17315376	698617	16004231	328992140	13273723	22799759	2590338	31863029	38224012	19614962
8	78542512.86	196660620	18181145	733548	16484358	345441747	13937409	23939747	2719854	31863029	43573546	20327381
9	80898788.25	206493651	19090202	770225	16978888	362713834	14634280	25136734	2855847	31863029	49245912	20885074
10	83325751.90	216818334	20044712	808737	17488255	380849526	15365994	26393571	2998640	31863029	55258912	21304703
11	85825524.46	227659251	21046947	849173	18012903	399892002	16134293	27713250	3148571	31863029	61631290	21601391
12	88400290.19	239042213	22099295	891632	18553290	419886602	16941008	29098912	3306000	31863029	68382774	21788859
13	91052298.89	250994324	23204260	936214	19109888	440880932	17788059	30553858	3471300	0	107397164	31109133
14	93783867.86	263544040	24364473	983024	19683185	462924979	18677462	32081551	3644865	0	114970266	30275264
15	96597383.90	276721242	25582696	1032176	20273681	486071228	19611335	33685628	3827108	0	122988121	29442378
16	99495305.41	290557304	26861831	1083784	20881891	510374789	20591901	35369910	4018464	0	131474948	28612779
17	102480164.58	305085169	28204923	1137973	21508348	535893529	21621496	37138405	4219387	0	140456239	27788518
18	105554569.51	320339428	29615169	1194872	22153598	562688205	22702571	38995325	4430356	0	149958821	26971412
19	108721206.60	336356399	31095927	1254616	22818206	590822615	23837700	40945092	4651874	0	160010926	26163065
20	111982842.80	353174219	32650723	1317347	23502752	620363746	25029585	42992346	4884468	0	170642260	25364885
∑	**1716002586.38**	**4621397979**	**427245193**	**17237902**	**360151454**	**8117658666**	**327520147**	**562568646**	**63914828**	**318630286**	**1610996887**	**498053892**

Annual running cost of CHP =	**211524411**				
Present value of annual running cost of CHP (£) =	**192294919**	**NPV =**	**252016031**		
Saving in CHP running cost over conventional running cost =	**52490018**	**IRR =**	**0.187**	**for NPV =**	**0.00**
Simple payback period SPBP =	**4.7**	**Years**			

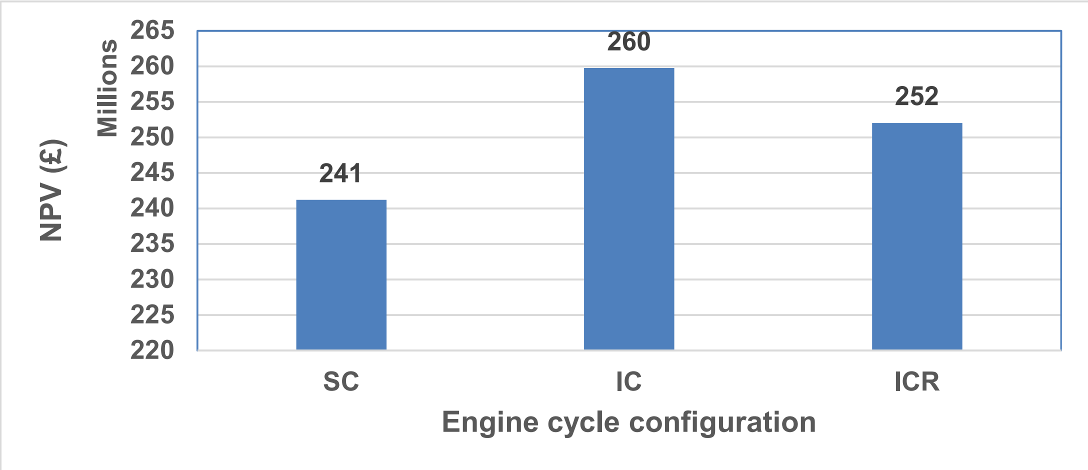


Figure 7-1 Net present value for LSRCP ADIGT-CHP

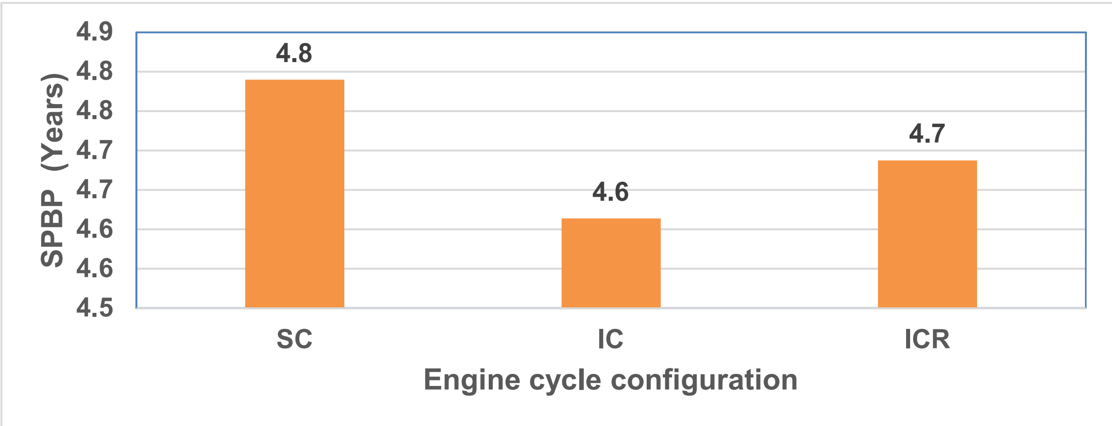


Figure 7-2 Simple payback period for LSRCP ADIGT-CHP

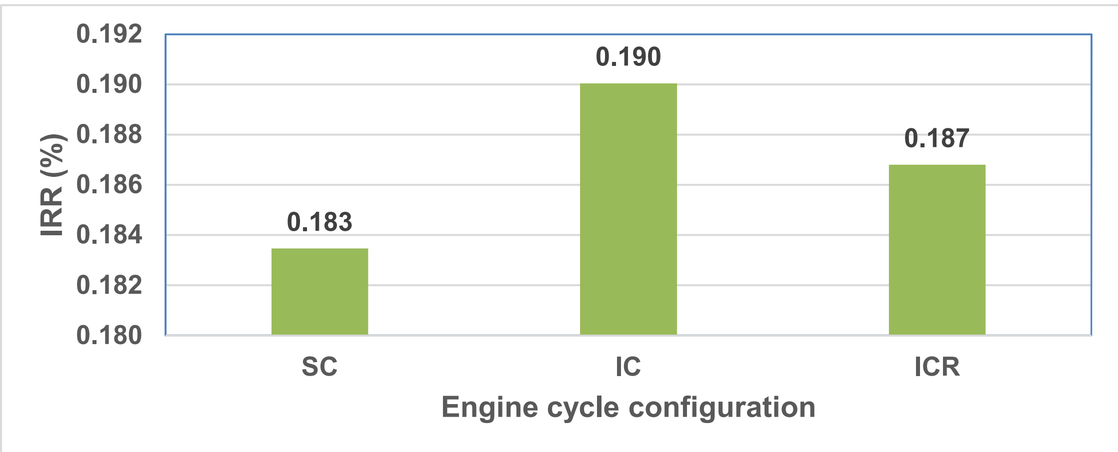


Figure 7-3 Internal rate of return for LSRCP ADIGT-CHP

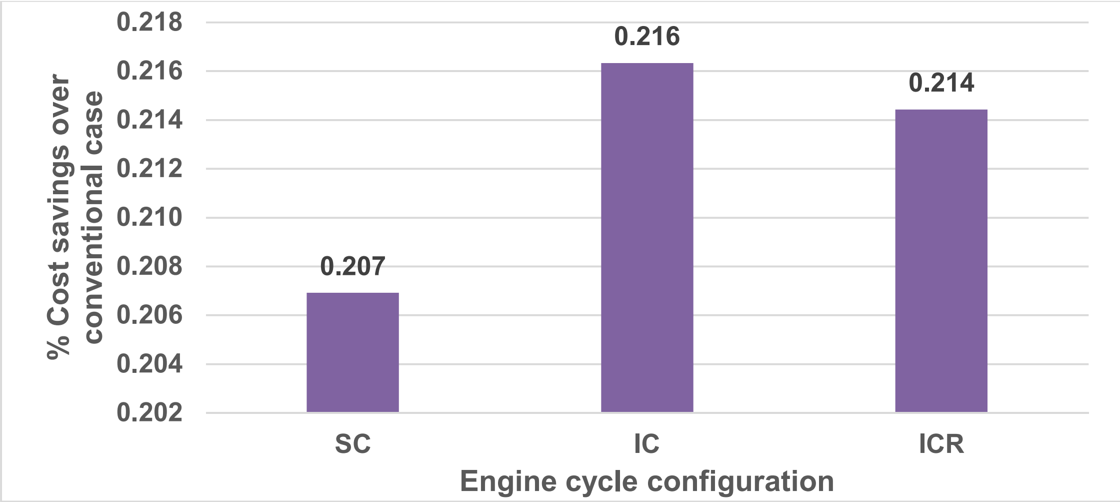


Figure 7-4 **Percentage cost savings of LSRCP ADIGT-CHP over conventional case**

7.2.4 Risk analysis of LSRCP ADIGT-CHP

Risk assessment of the LSRCP ADIGT-CHP is accomplished by integrating the software @Risk 6.0 to perform Latin Hypercube sampling (a modified Monte Carlo simulation) of 10,000 random number generations of values of some inputs. This is done to determine the effects on NPV of changes in values of the inputs.

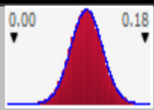
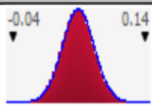
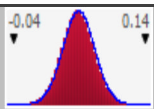
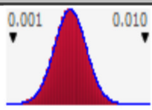
7.2.4.1 Probability distributions of inputs for LSRCP CHP

Grid electricity price, gas turbine gas fuel price, electricity export price, and emission tax, are identified as economic inputs of high uncertainty. So their probability effects on NPV are simulated for the three various engine cycles. Three types of probability distributions are studied, namely, normal, triangular, and uniform distributions.

7.2.4.1.1 Normal distribution of inputs for LSRCP CHP

Normal frequency distributions are defined for the inputs as presented in Table 7-9. These inputs distributions are maintained in the risk simulation for the SC, IC, and ICR cycles ADIGT-CHP of LSRCP.

Table 7-9 Normal distribution of inputs defined for LSRCP CHP

Inputs	Normal graph	standard deviation (σ)	Minimum	Mean	Maximum	5th percen tile	95th percen tile
Electricity tariff from grid £/kWhe:		0.02	0.003	0.01	0.177	0.067	0.133
Electricity export tariff to grid £/kWhe :		0.02	-0.028	0.05	0.125	0.017	0.083
GT gas fuel price (£/kWh):		0.02	-0.026	0.05	0.128	0.017	0.083
Emission tax £/kg :		0.001	-0.001	0.005	0.009	0.003	0.007

7.2.4.1.2 Results of normal distribution risk analysis for LSRCP CHP

The results of normal probability distributions of NPV for the three engine cycles are presented in Figure 7-5, Figure 7-6, and Figure 7-7.

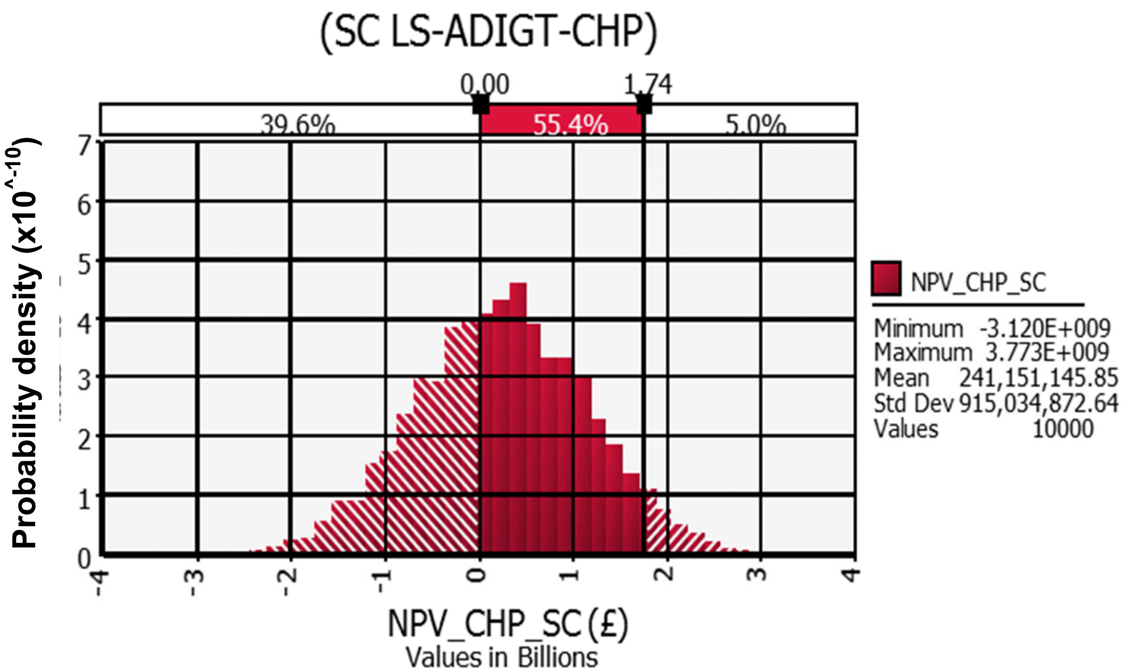


Figure 7-5 Normal probability distribution of NPV for SC, LS-ADIGT-CHP (LSRCP)

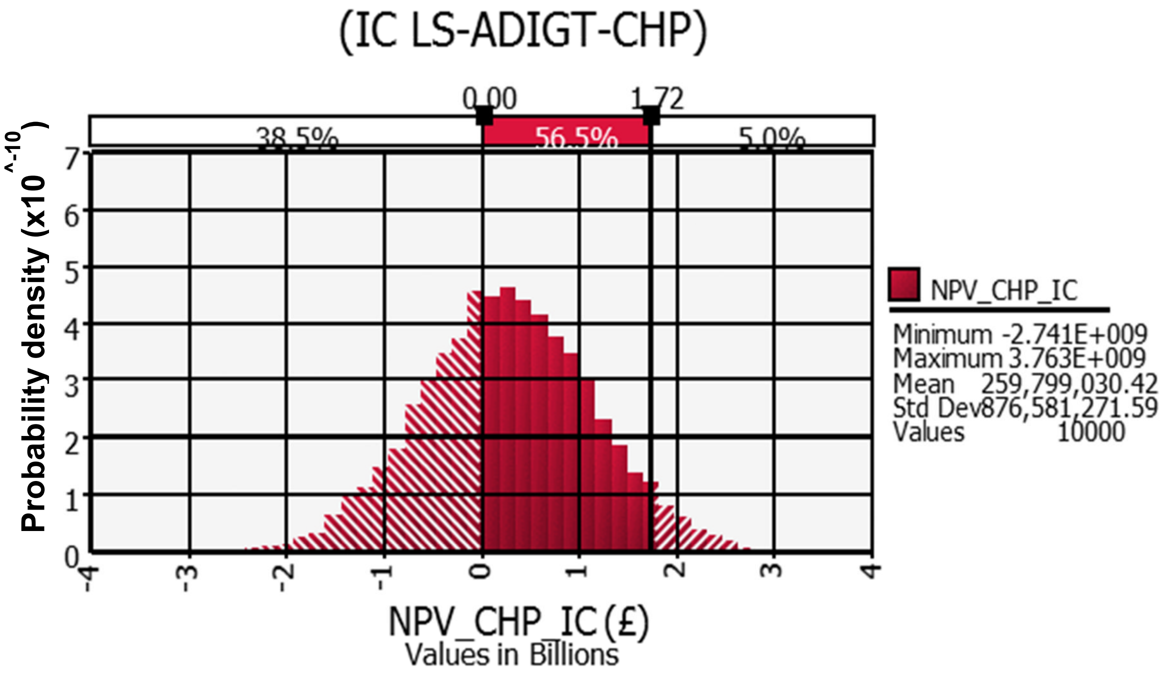


Figure 7-6 Normal probability distribution of NPV for IC, LS-ADIGT-CHP (LSRCP)

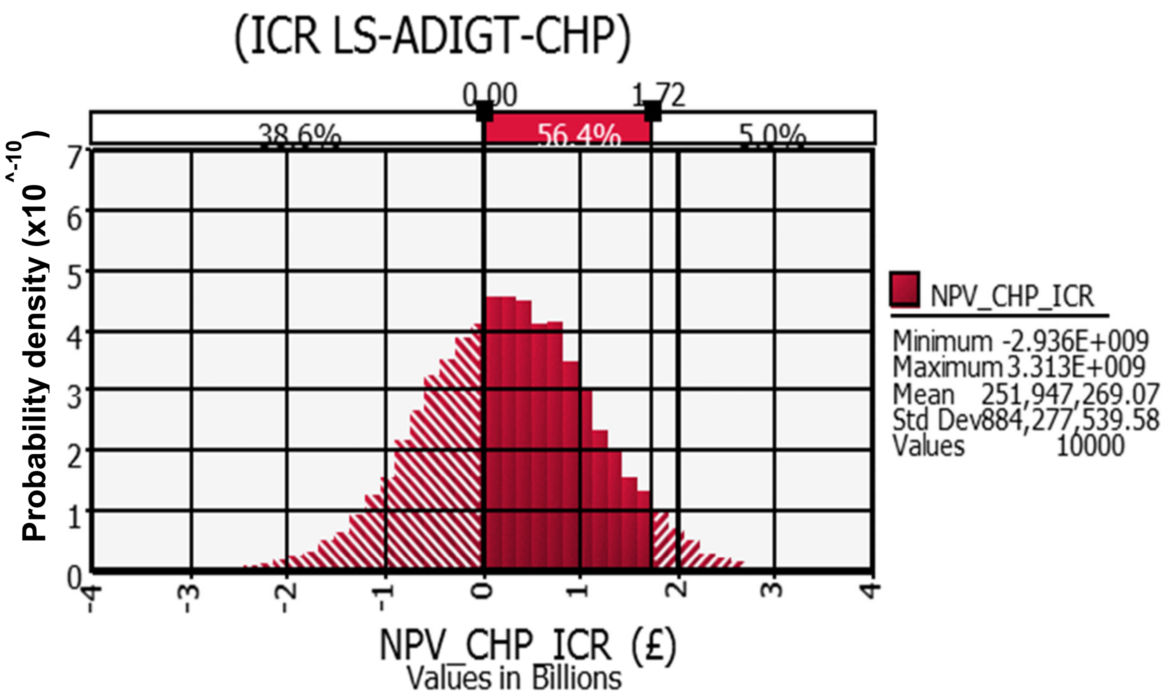


Figure 7-7 Normal probability distribution of NPV for ICR, LS-ADIGT-CHP (LSRCP)

The results of sensitivity of NPV to variations in values of inputs are shown in Figure 7-8, Figure 7-9, and Figure 7-10

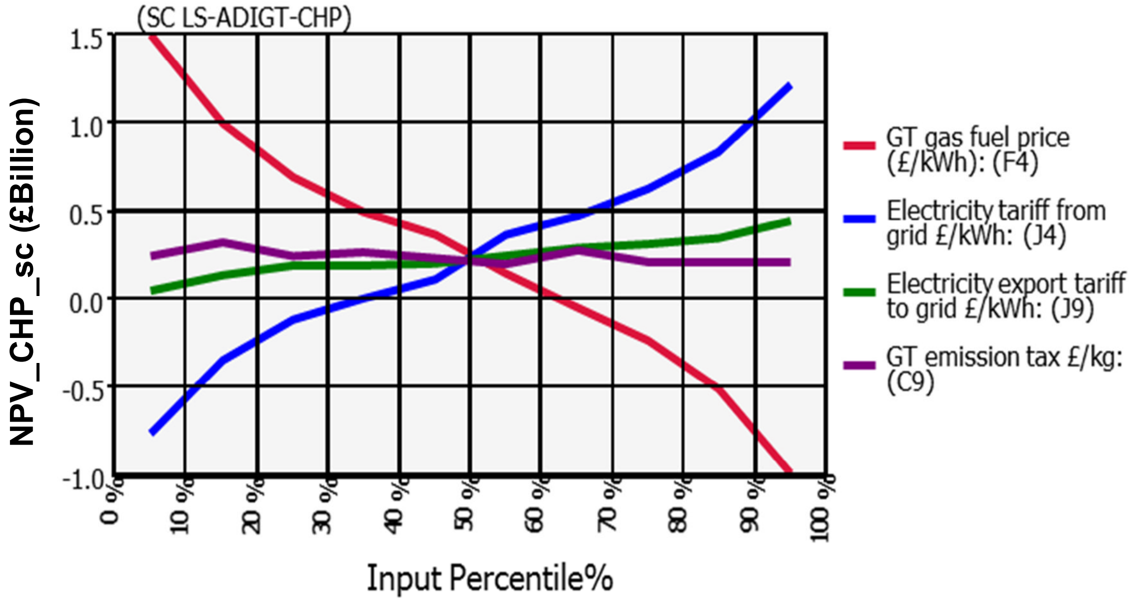


Figure 7-8 Sensitivity of NPV to changes in inputs values for SC, LS-ADIGT-CHP of LSRCP (Normal distribution)

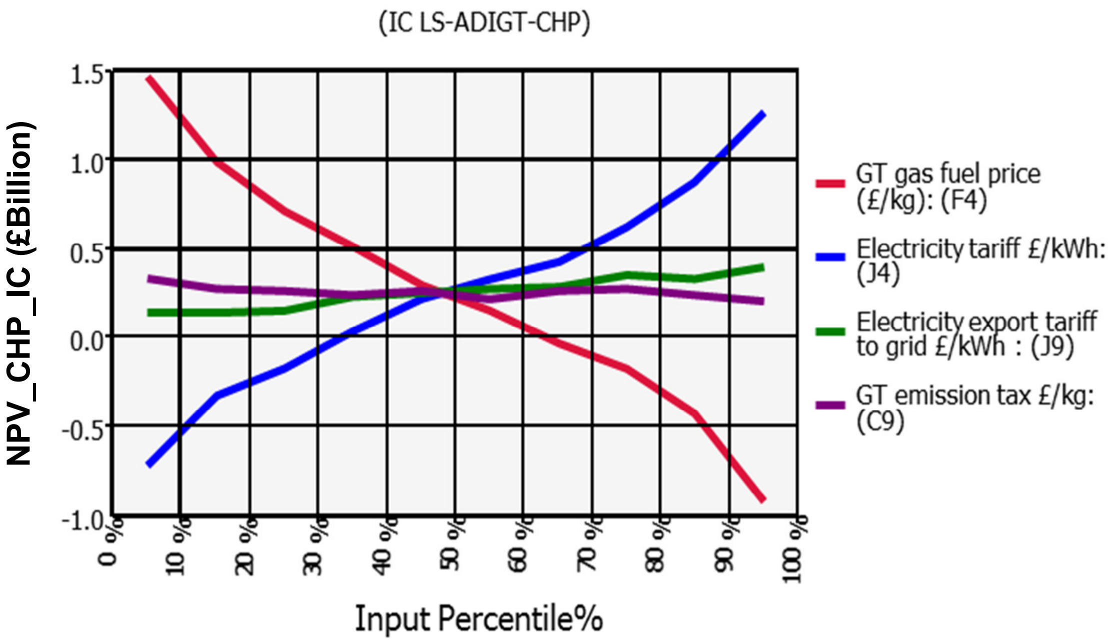


Figure 7-9 Sensitivity of NPV to changes in inputs values for IC, LS-ADIGT-CHP of LSRCP (Normal distribution)

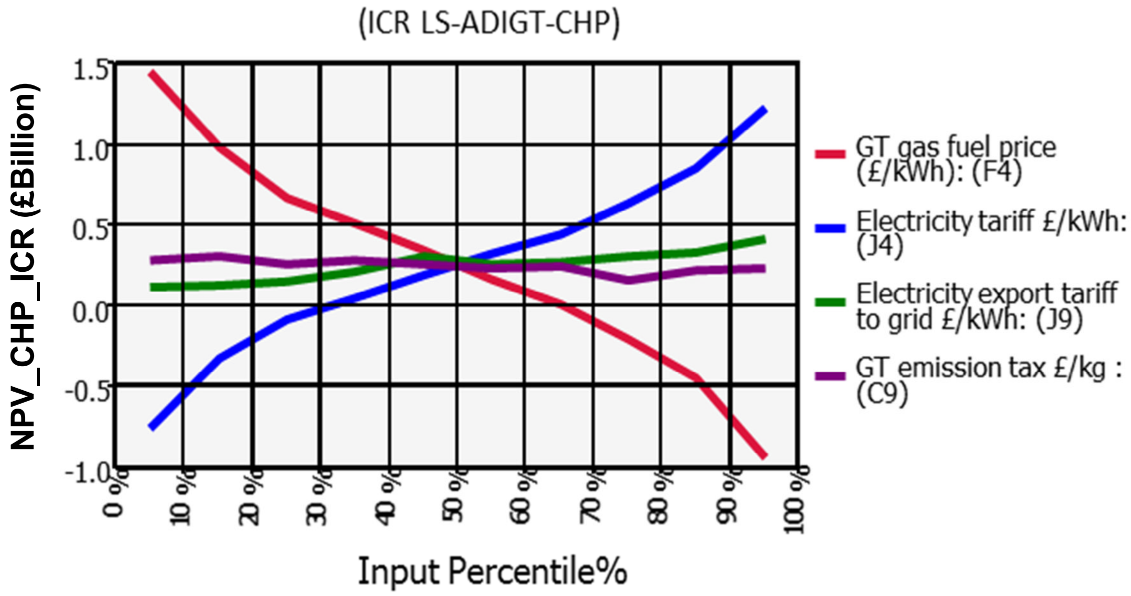


Figure 7-10 Sensitivity of NPV to changes in inputs values for ICR, LS-ADIGT-CHP of LSRCP (Normal distribution)

The ranking of inputs by their effects on NPV is shown in Figure 7-11, Figure 7-12, and Figure 7-13.

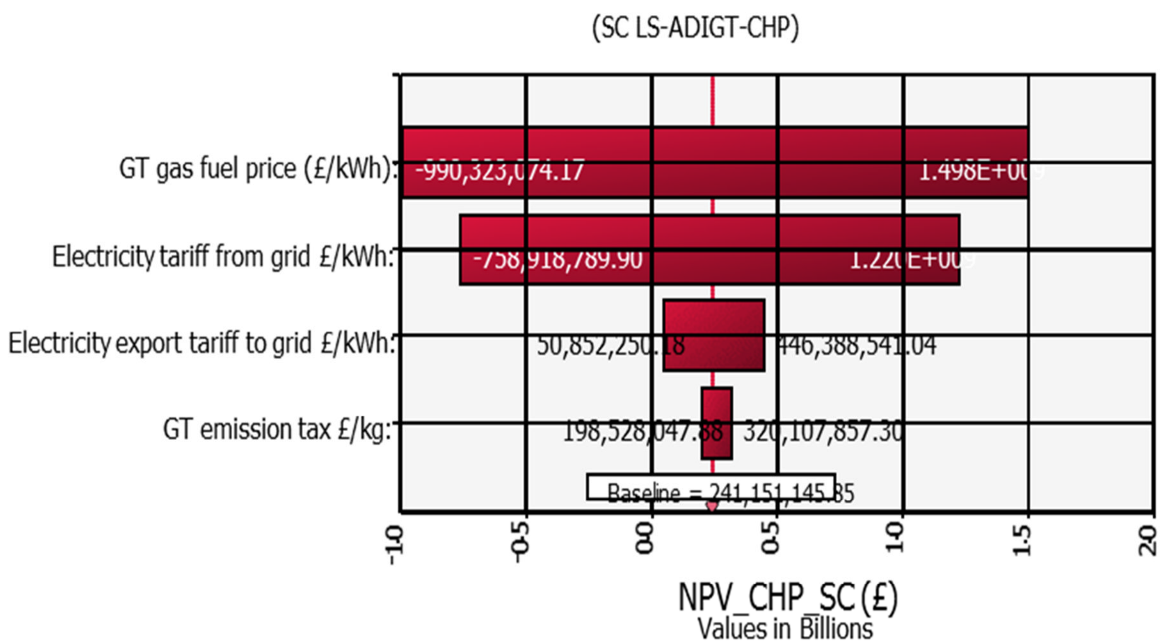


Figure 7-11 Inputs ranked by effects on NPV for SC, LS-ADIGT-CHP of LSRCP (Normal distribution)

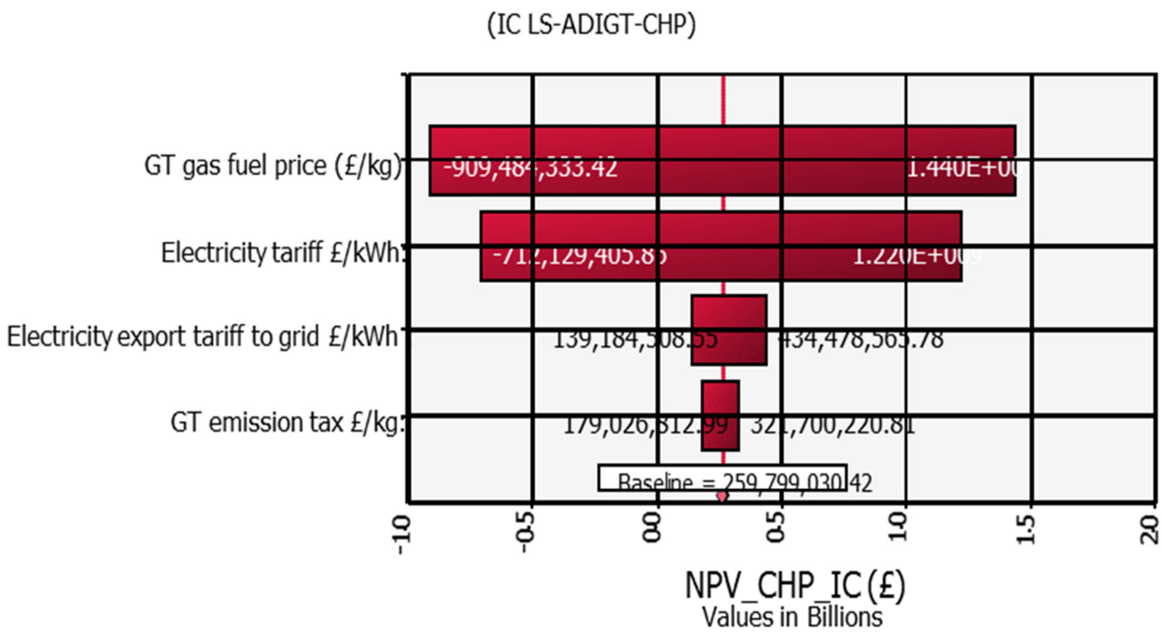


Figure 7-12 Inputs ranked by effects on NPV for IC, LS-ADIGT-CHP of LSRCP (Normal distribution)

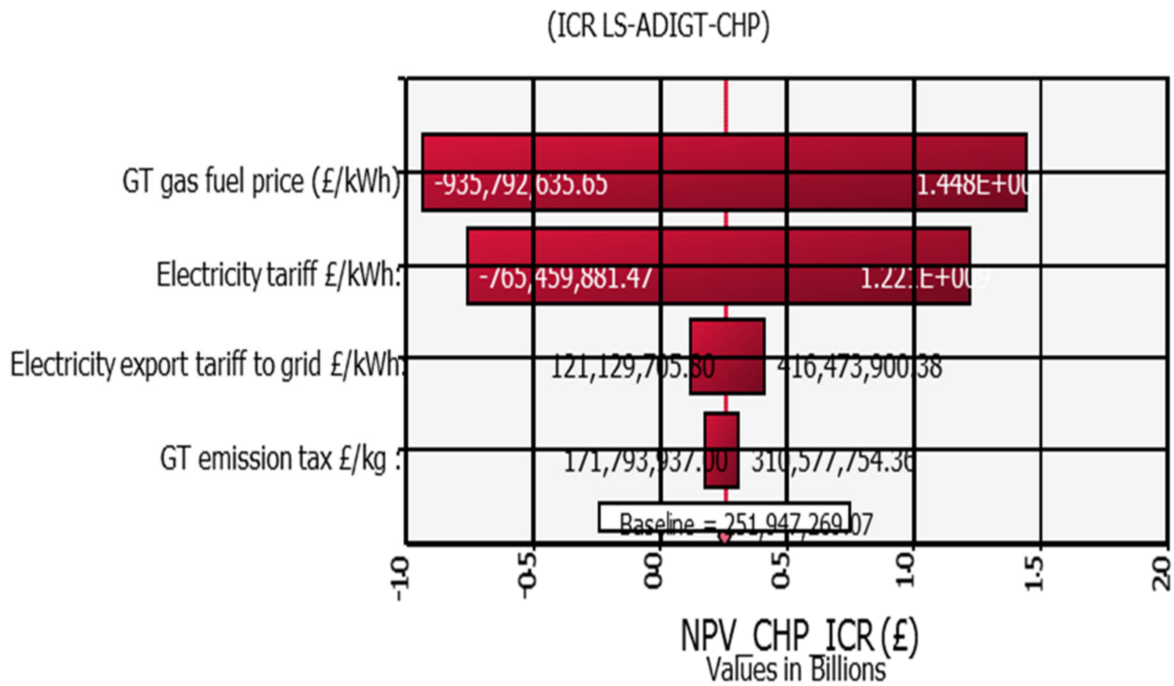


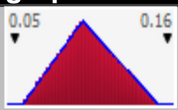
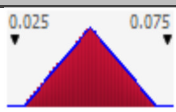
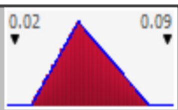
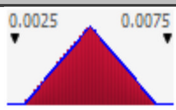
Figure 7-13 Inputs ranked by effects on NPV for ICR, LS-ADIGT-CHP of LSRCP (Normal distribution)

From the normal distribution results the probability of having less than zero or zero NPV which is the range for making loss in investment is obtained as 39.6% for SC, 38.5% for IC, and 38.6% for ICR. This is shown in Figure 7-5 to Figure 7-7. These values are actually high in reality, but the idea here is not about pegging the design for low probability, instead the aim of the analysis is to formulate a procedure or method of assessment and comparing performance of engine cycles.

7.2.4.1.3 Triangular distribution of inputs for LSRCP CHP

Triangular frequency distributions are defined for the inputs as presented in Table 7-10

Table 7-10 Triangular distribution of inputs defined for LSRCP CHP.

Inputs	Triangular graph	Minimum	Mean	Maximum	5th percentile	95th percentile
Electricity tariff from grid £/kWhe:		0.06	0.1	0.15	0.073	0.135
Electricity export tariff to grid £/kWhe :		0.03	0.05	0.07	0.036	0.064
GT gas fuel price (£/kWh):		0.03	0.05	0.08	0.037	0.071
Emission tax £/kg :		0.003	0.005	0.007	0.0036	0.0064

7.2.4.1.4 Results of triangular distribution risk analysis for LSRCP CHP

Following the same procedure of section 7.2.4.1.1, the results of probability distributions of NPV for the three engine cycles are presented in Figure 7-14 to Figure 7-16. Besides, the results of sensitivity of NPV to variations in values of inputs are shown in Figure 7-17 to Figure 7-19, whereas the ranking of inputs by their effects on NPV is shown in Figure 7-20 to Figure 7-22.

From the triangular distribution results the probability of having less than zero or zero NPV which is the range for making loss in investment is obtained as 37.3% for SC, 35.9% for IC, and 36.8% for ICR. This is evident from Figure 7-14 to Figure 7-16.

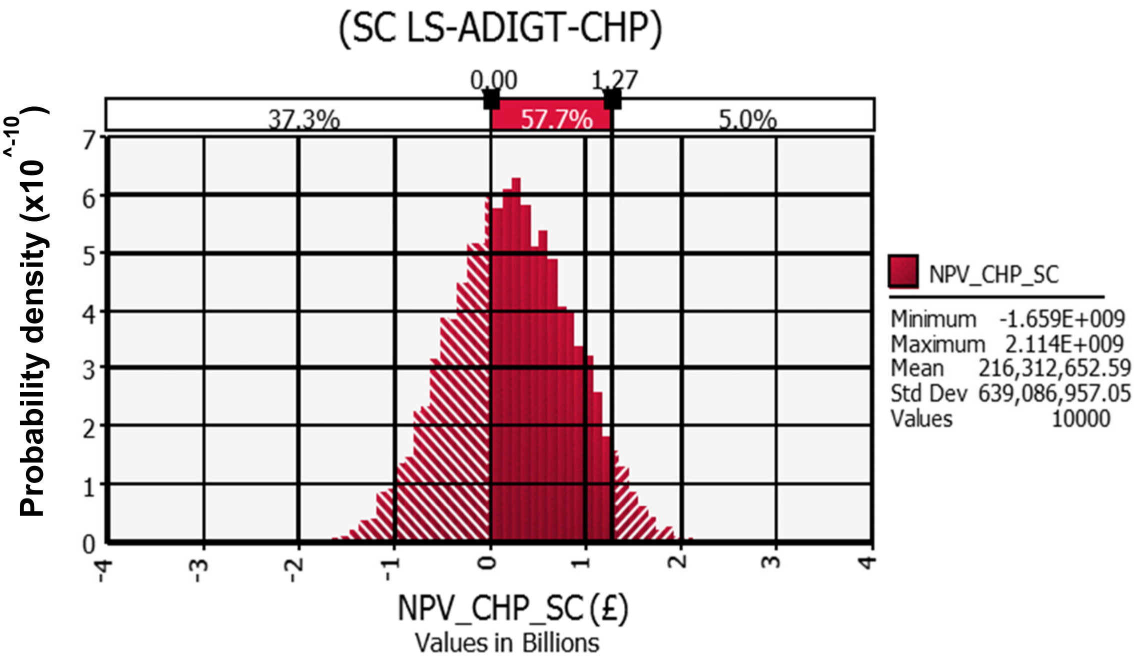


Figure 7-14 Triangular probability distribution of NPV for SC, LS-ADIGT-CHP of LSRCP

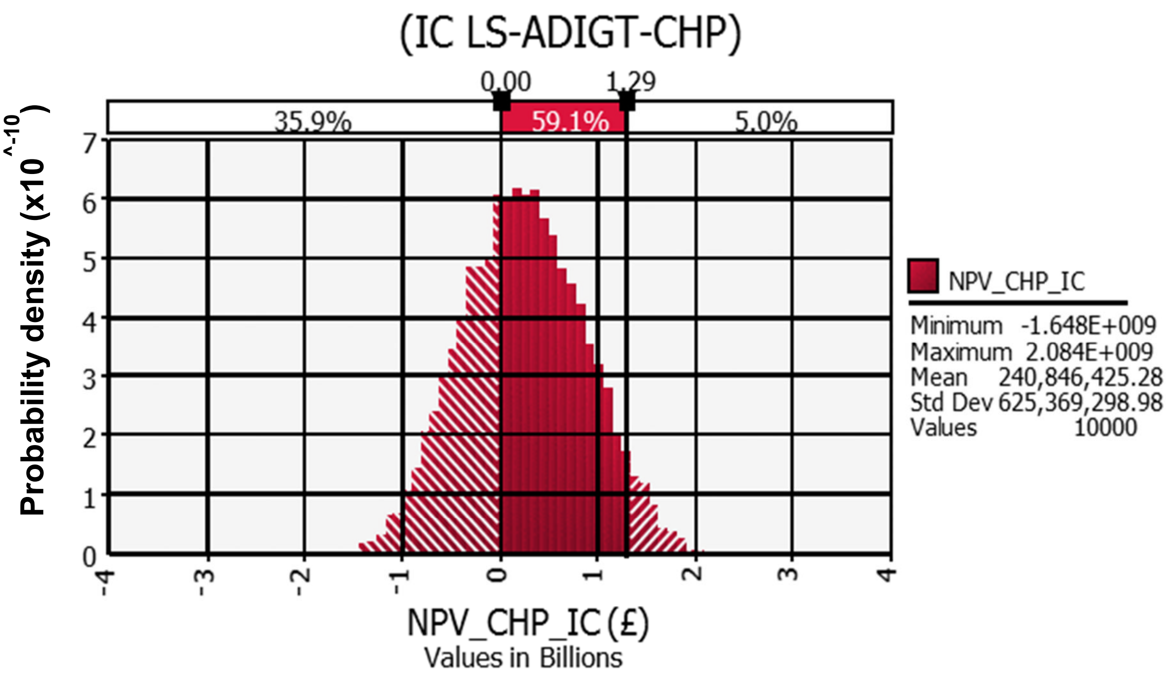


Figure 7-15 Triangular probability distribution of NPV for IC, LS-ADIGT-CHP of LSRCP

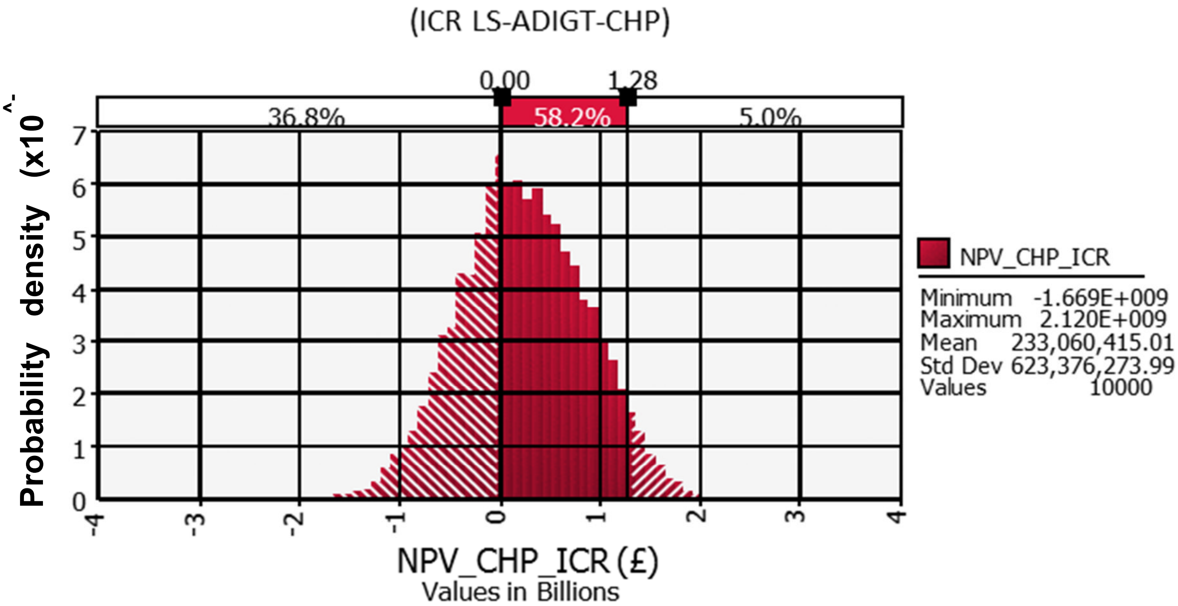


Figure 7-16 Triangular probability distribution of NPV for ICR, LS-ADIGT-CHP of LSRCP

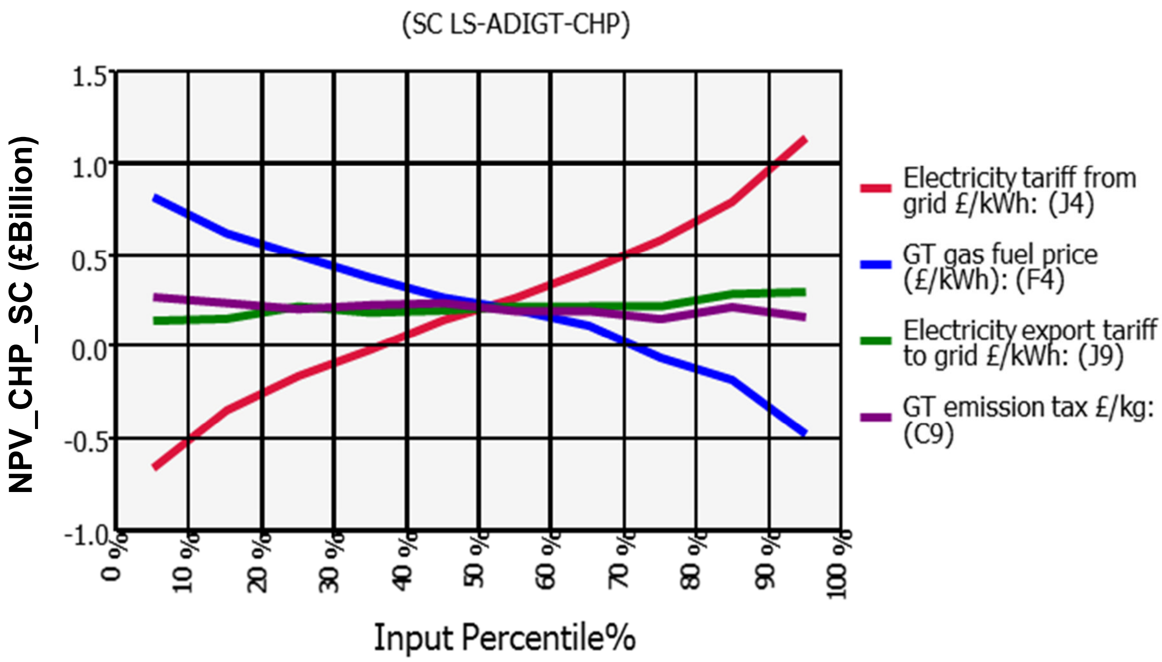


Figure 7-17 Sensitivity of NPV to changes in inputs values for SC, LS-ADIGT-CHP of LSRCP (Triangular distribution)

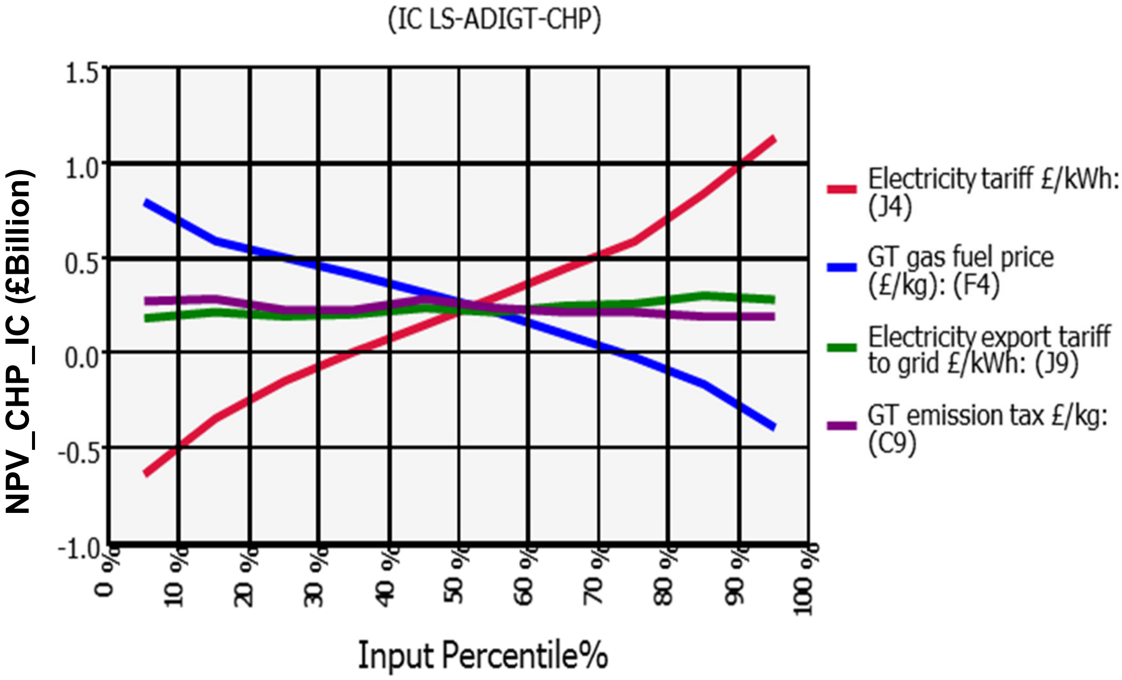


Figure 7-18 Sensitivity of NPV to changes in inputs values for IC, LS-ADIGT-CHP of LSRCP (Triangular distribution)

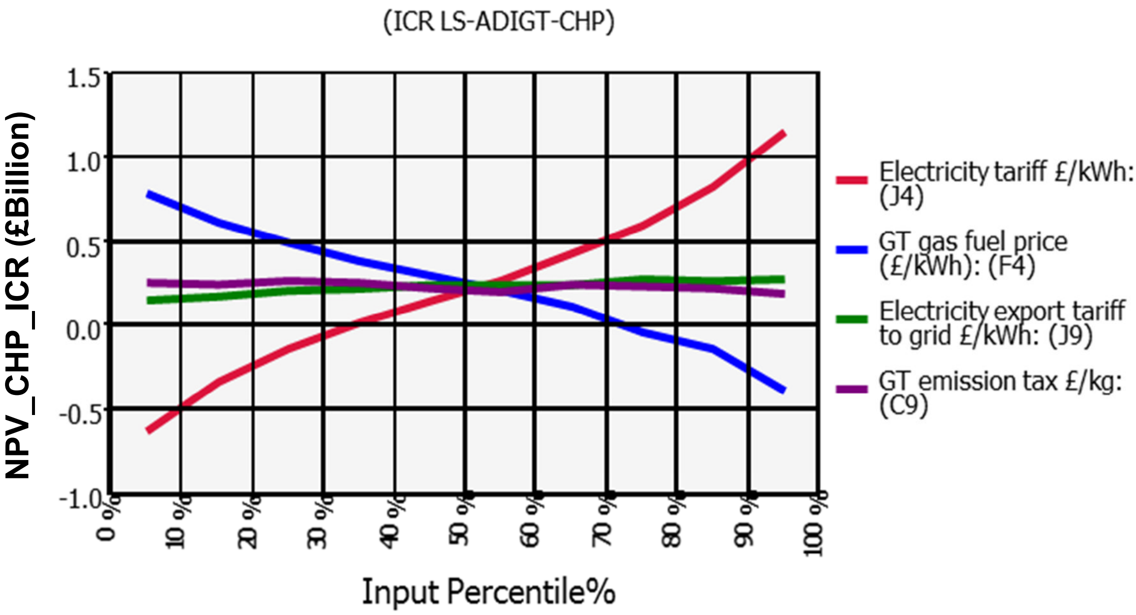


Figure 7-19 Sensitivity of NPV to changes in inputs values for ICR, LS-ADIGT-CHP of LSRCP (Triangular distribution)

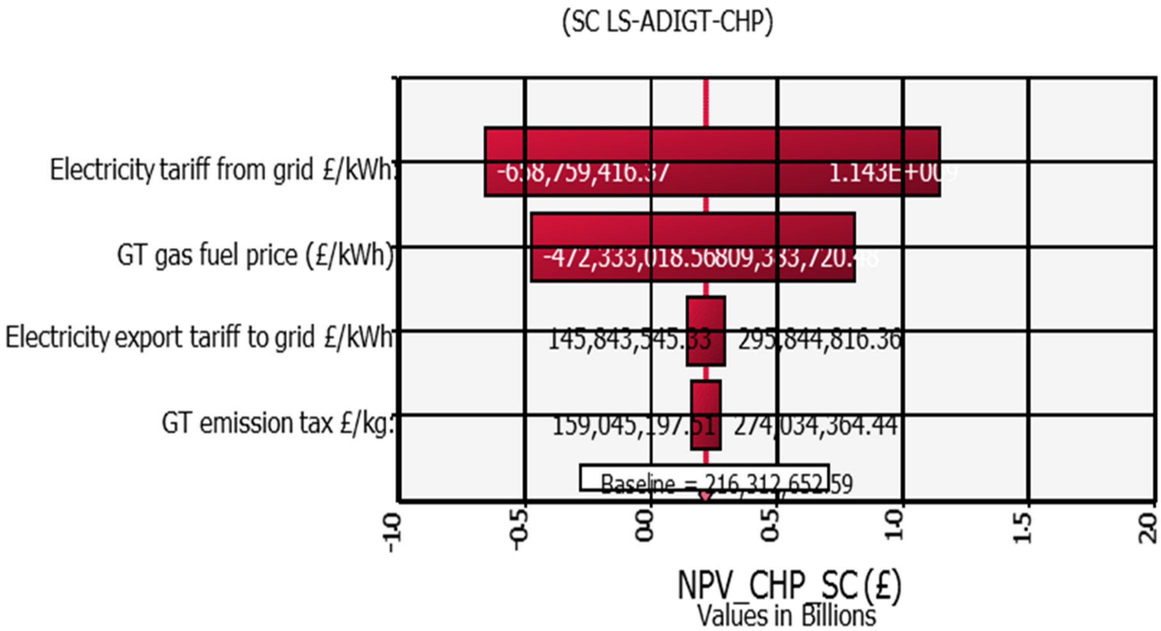


Figure 7-20 Inputs ranked by effects on NPV for SC LS-ADIGT-CHP of LSRCP (Triangular distribution)

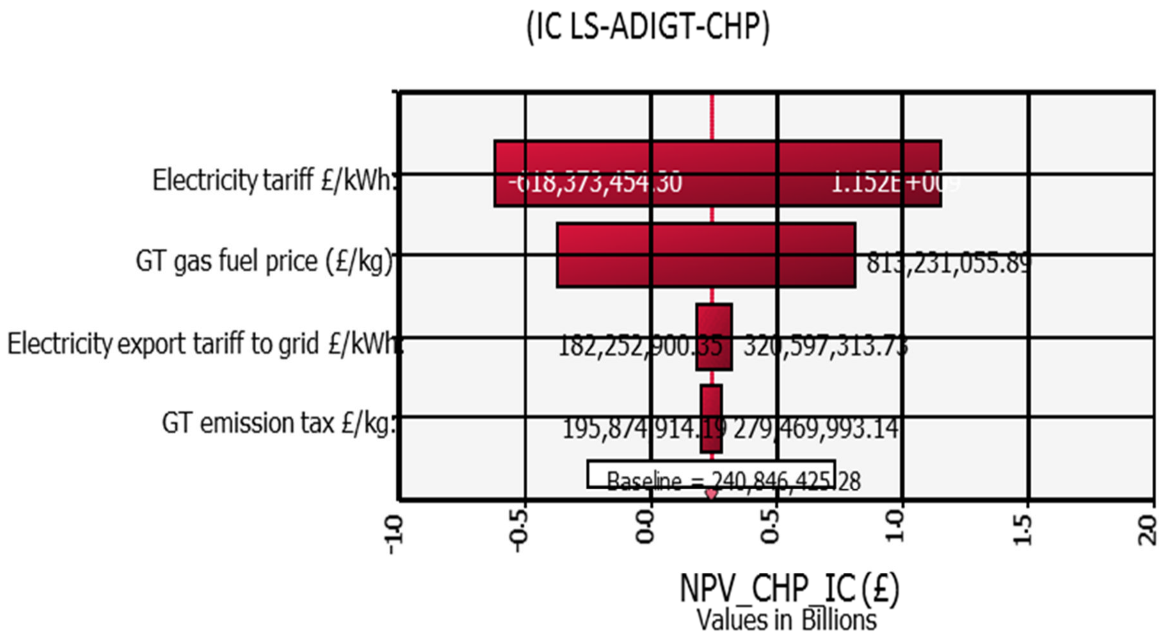


Figure 7-21 Inputs ranked by effects on NPV for IC LS-ADIGT-CHP of LSRCP (Triangular distribution)

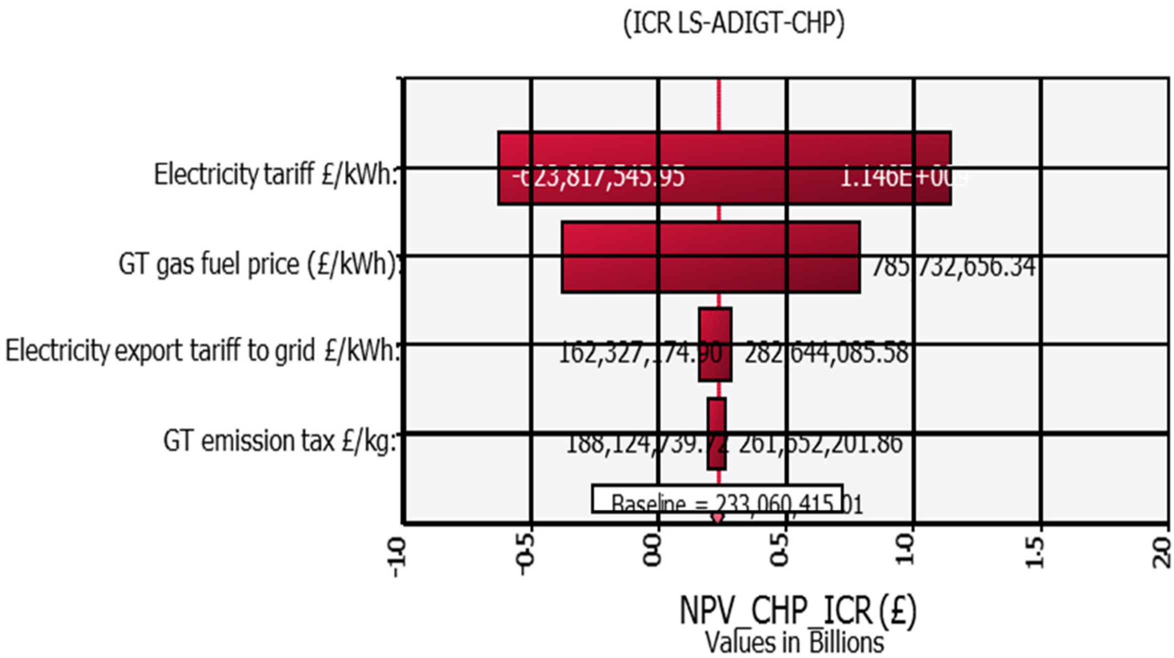
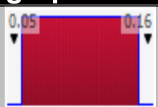
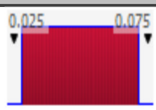
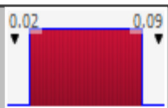
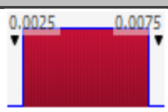


Figure 7-22 Inputs ranked by effects on NPV for ICR LS-ADIGT-CHP of LSRCP (Triangular distribution)

7.2.4.1.5 Uniform distribution of inputs for LSRCP CHP

Uniform frequency distributions are defined for the inputs as presented in Table 7-11

Table 7-11 Uniform distribution of inputs defined for LSRCP CHP.

Inputs	Uniform graph	Minimum	Mean	Maximum	5th percentile	95th percentile
Electricity tariff from grid £/kWhe:		0.06	0.1	0.15	0.064	0.145
Electricity export tariff to grid £/kWhe :		0.03	0.05	0.07	0.032	0.068
GT gas fuel price (£/kWh):		0.03	0.05	0.08	0.032	0.078
Emission tax £/kg :		0.003	0.005	0.007	0.032	0.068

7.2.4.1.6 Results of uniform distribution risk analysis for LSRCP CHP

Following the same procedure of section 7.2.4.1.1, the results of probability distributions of NPV for the three cycles are presented in Figure 7-23 to Figure 7-25.

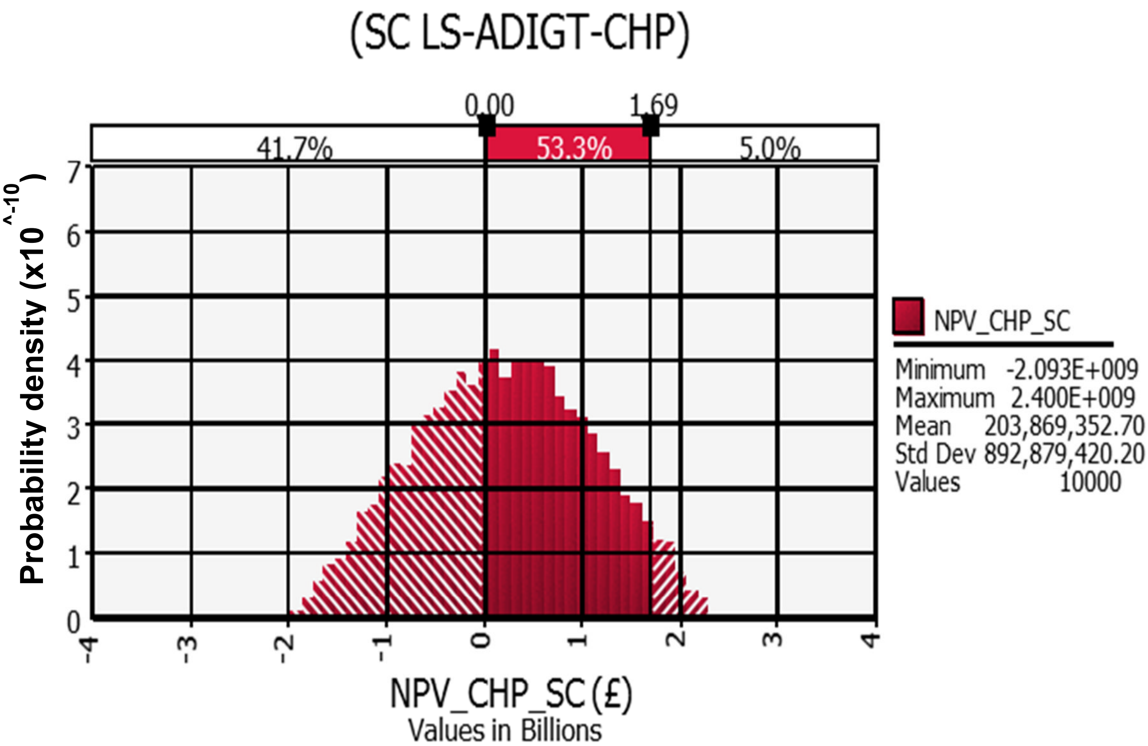


Figure 7-23 Uniform probability distribution of NPV for SC LS-ADIGT-CHP of LSRCP

The results of sensitivity of NPV to variations in values of inputs are shown in Figure 7-26 to Figure 7-28, whereas the ranking of inputs by their effects on NPV is shown in Figure 7-29 to Figure 7-31.

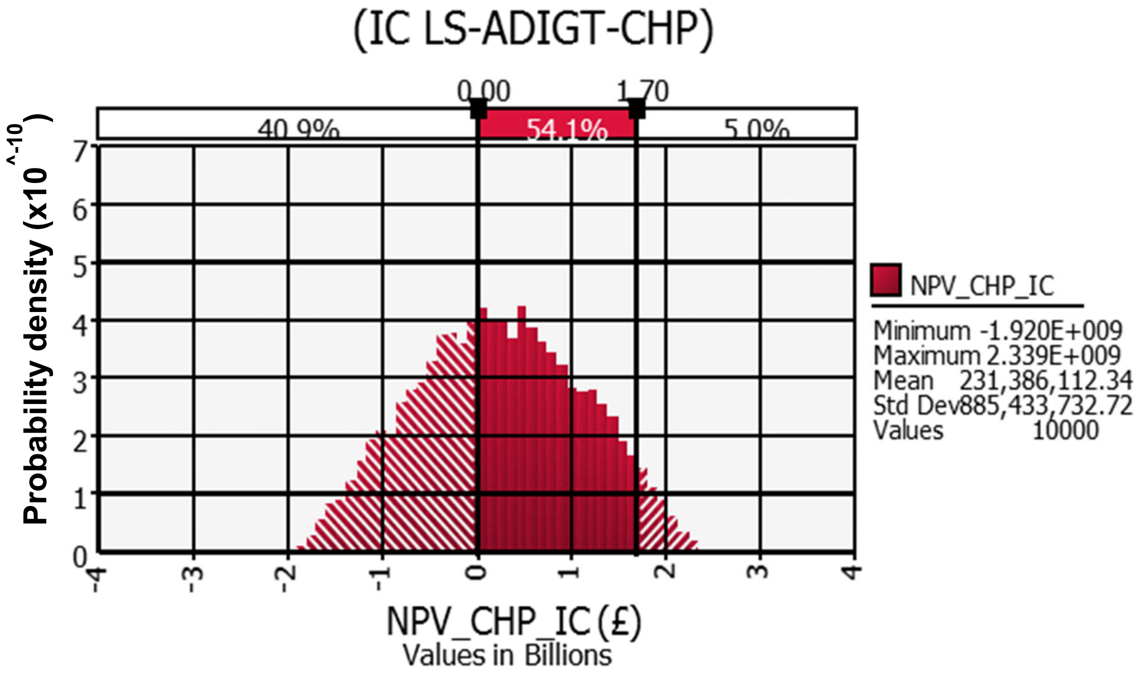


Figure 7-24 Uniform probability distribution of NPV for IC LS-ADIGT-CHP of LSRCP

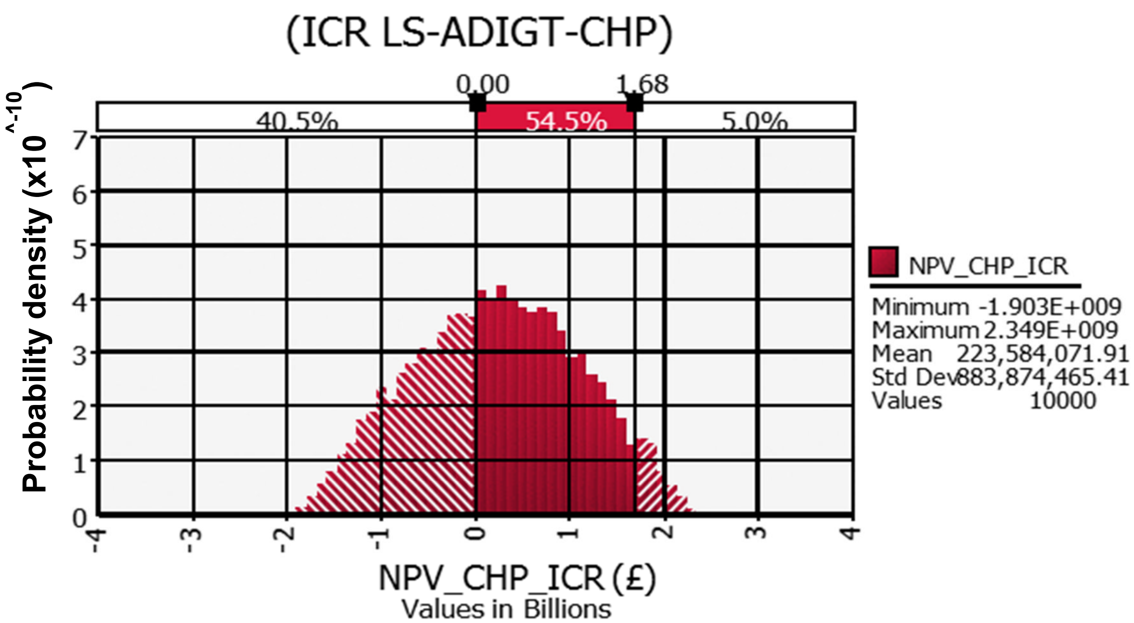


Figure 7-25 Uniform probability distribution of NPV for ICR LS-ADIGT-CHP of LSRCP

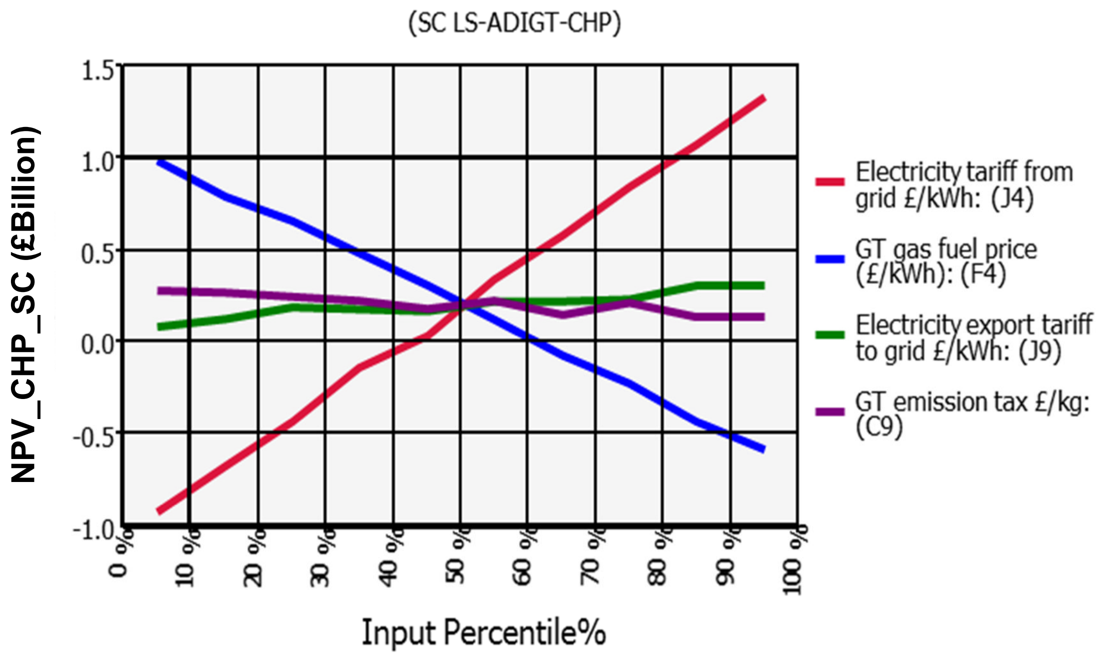


Figure 7-26 Sensitivity of NPV to changes in inputs values for SC LS-ADIGT-CHP of LSRCP (Uniform distribution)

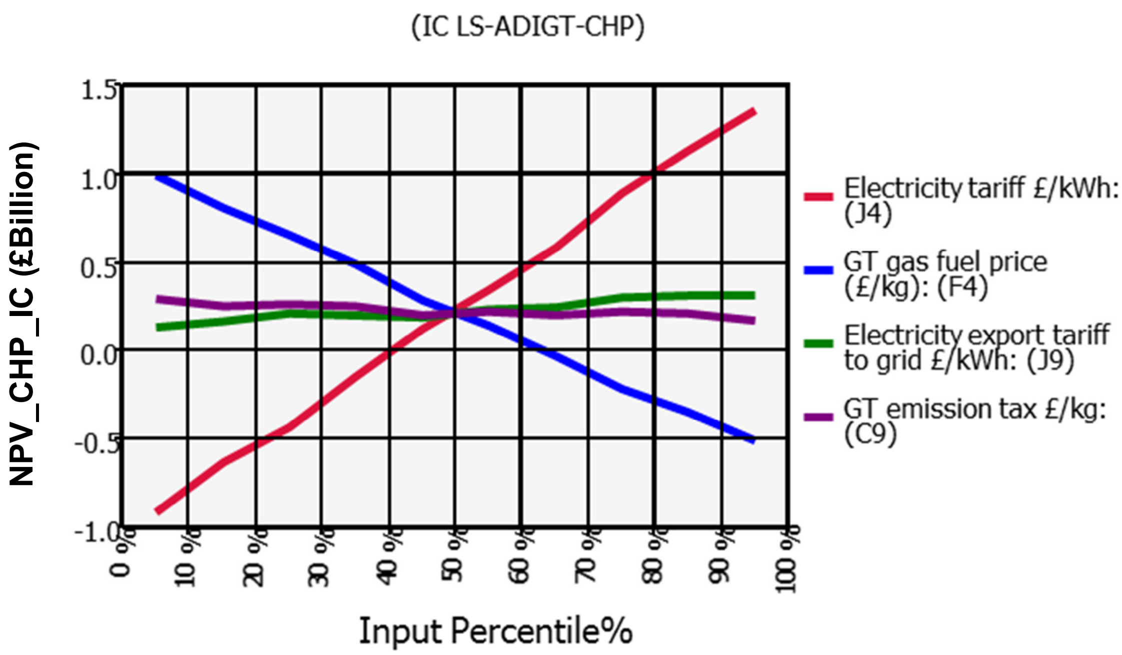


Figure 7-27 Sensitivity of NPV to changes in inputs values for IC LS-ADIGT-CHP of LSRCP (Uniform distribution)

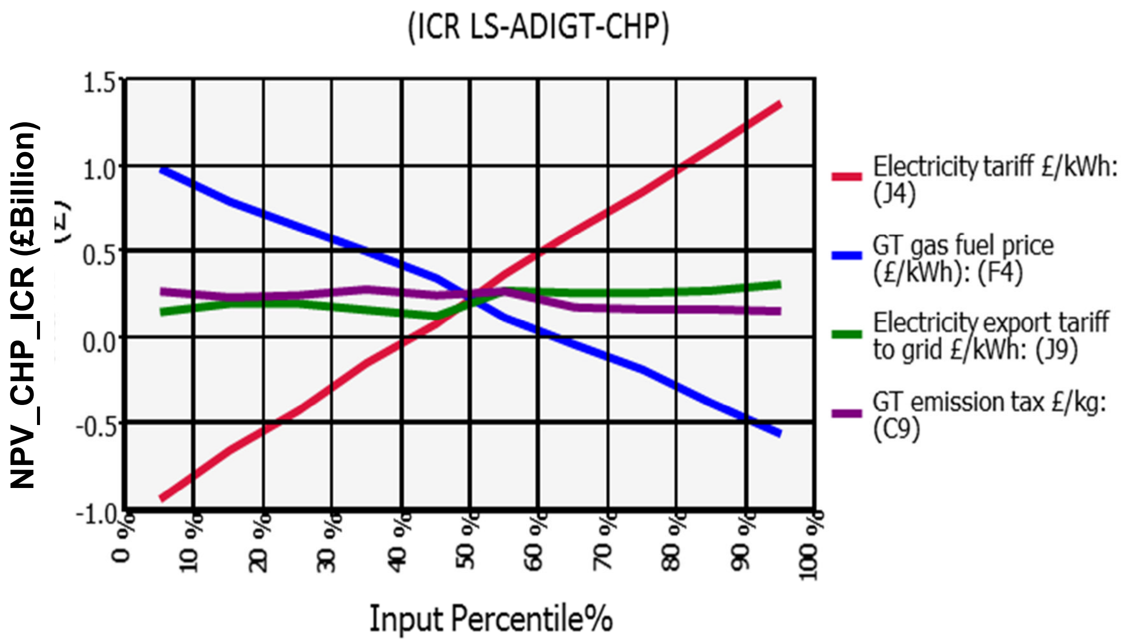


Figure 7-28 Sensitivity of NPV to changes in inputs values for ICR LS-ADIGT-CHP of LSRCP (Uniform distribution)

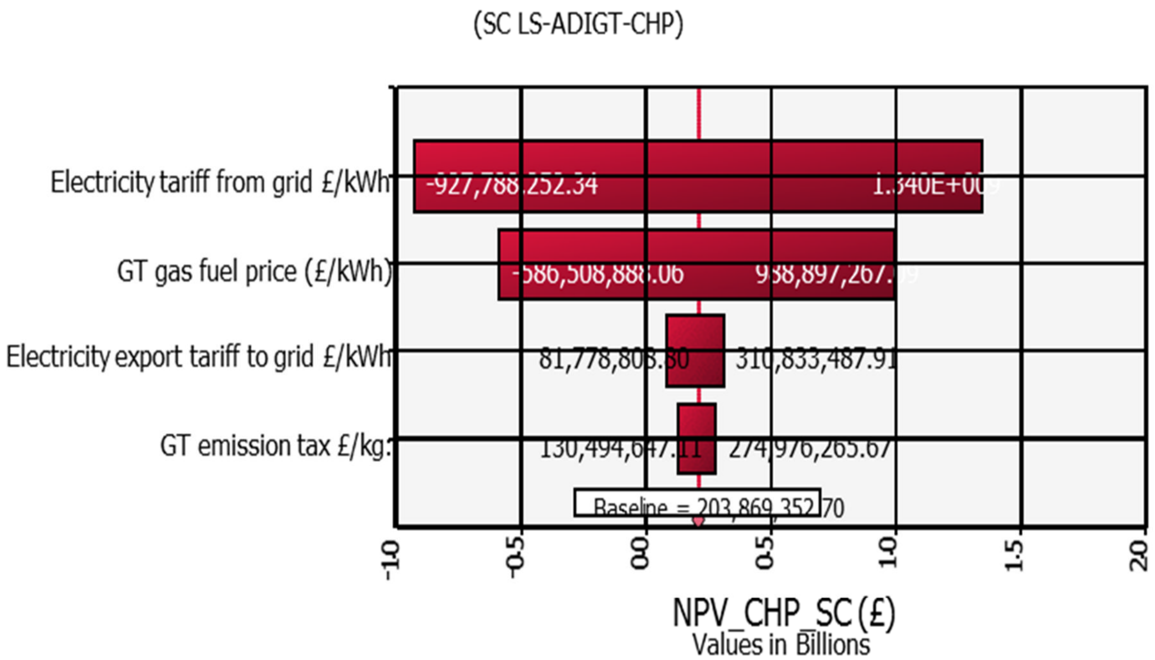


Figure 7-29 Inputs ranked by effects on NPV for SC LS-ADIGT-CHP of LSRCP (Uniform distribution)

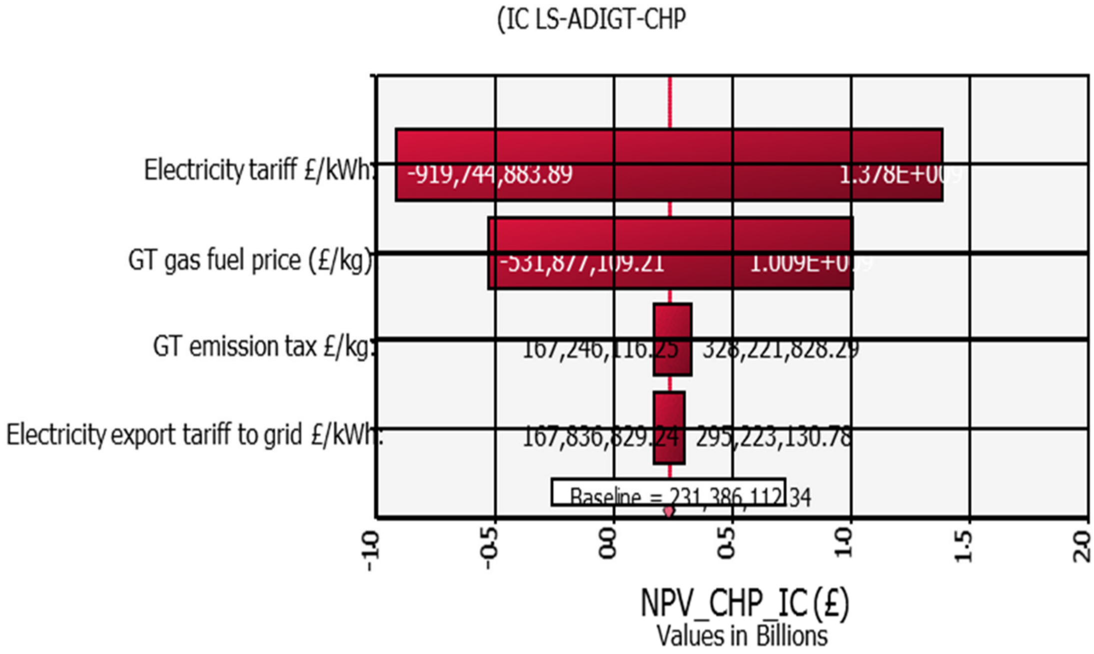


Figure 7-30 Inputs ranked by effects on NPV for IC LS-ADIGT-CHP of LSRCP (Uniform distribution)

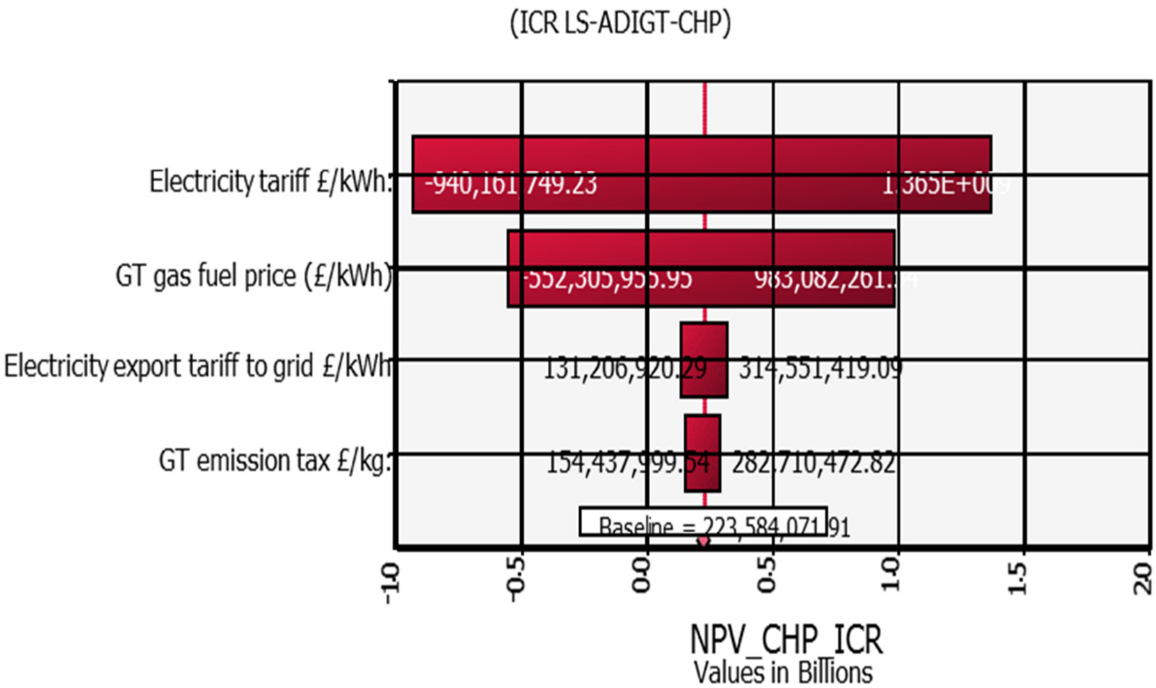


Figure 7-31 Inputs ranked by effects on NPV for ICR LS-ADIGT-CHP of LSRCP (Uniform distribution)

From the uniform distribution results the probability of having less than zero or zero NPV which is the range for making loss in investment is obtained as 41.7% for SC, 40.9% for IC, and 40.5% for ICR as shown in Figure 7-23 to Figure 7-25.

7.2.4.1.7 NPV sensitivity analysis results of LSRCP ADIGT-CHP

Sensitivity analysis of NPV for LSRCP ADIGT-CHP shows that change in grid electricity price has the greatest effect on mean NPV followed by that of gas turbine fuel price, whereas variation in electricity export price has the least effect for all three engine cycles as shown in Figure 7-11 to Figure 7-13, Figure 7-20 to Figure 7-22, and Figure 7-29 to Figure 7-31. This trend is replicated for normal, triangular, and uniform distribution of inputs.

Similarly, for all three types of distributions, it is also observed that as price of electricity from grid increases (depicted by increasing input percentile) mean NPV increases for all three engine cycles as shown in Figure 7-8 to Figure 7-10, Figure 7-17 to Figure 7-19, and Figure 7-26 to Figure 7-28. This is because the main benefit of the CHP plant is to save cost of purchasing power from the grid. Of course this trend is expected because the higher the grid electricity price, the higher the saved cost of grid electricity which adds to annual net savings. Also from the annual power generation/consumption of the plant, power purchased from the grid is far lower than power generated on site annually, hence the huge amount in saved grid electricity cost. More so, mean NPV increases very slightly with increase in electricity export price because very minute quantity of electricity is exported. On the other hand, as gas turbine fuel price increases, mean NPV decreases. This is true as gas turbine fuel price is huge expense. Change in emission tax has very little or insignificant effect on mean NPV perhaps due to the minute amount of the unit price paid as emission penalty.

Still explaining the sensitivity curves of Figure 7-8 to Figure 7-10, Figure 7-17 to Figure 7-19, and Figure 7-26 to Figure 7-28, it could be observed that mean NPV occurs in the scenario of input values that fall in the 50th percentile of input distributions. For scenario of input values above the 50th percentile (51% - 95%) of input distributions, and for same reasons as stated in the above paragraph, it is found that: NPV increases above the mean value with grid power tariff; decreases below mean value with GT fuel price; increases very slightly with electricity export price; and decreases very slightly with GT emission tax. On the other hand, for scenario of input values below the 50th percentile (5% - 49%) of input distributions, NPV becomes lower than the mean value with grid power tariff; increases above the mean value with GT fuel price; decreases very slightly with electricity export price; and increases very slightly with GT emission tax. The import of these results is that GT fuel price and grid power tariff are very significant input quantities in the life-cycle cost of the CHP project, and therefore require further priority attention and investigation.

Sensitivity analysis results of the triangular and uniform distribution simulation are similar to those of normal distribution, except that the range of values of mean NPV is narrower in the case of uniform distribution, and narrowest in the case of triangular distribution. Nevertheless, probability density of mean NPV is higher in the case of uniform distribution than normal distribution, and highest in the case of triangular distribution. This explains why the sensitivity curves are less steep in the case of triangular distribution. This difference is evident in Figure 7-8 to Figure 7-10, Figure 7-17 to Figure 7-19, and Figure 7-26 to Figure 7-28.

7.2.5 Overall results for LSRCP ADIGT-CHP economic analysis

The outcome of the techno-economic assessment of the LSRCP-CHP indicates that all three cycle configurations, SC, IC, and ICR LS-ADIGT-CHP register positive NPV and are profitable than the conventional case. However, the case of IC LS-ADIGT-CHP yielded the highest profit in NPV, the shortest payback period, and the highest IRR, followed by the ICR LS-ADIGT-CHP. These are shown in Figure 7-1 to Figure 7-3. It was found that the percentage savings in operational cost of SC, IC, and ICR cycle LS-ADIGT–CHP over and above the conventional case (grid power plus on-site boiler) are 20.7%, 21.6%, and 21.4% respectively as presented in Figure 7-4. Sales of excess electricity and steam are observed to be huge in the case of SC LS-ADIGT-CHP than in IC and ICR LS-ADIGT-CHP. The much excess steam is as a result of high temperature-high heat content of the exhaust gas of the SC LS-ADIGT compared to those of the IC and ICR cycles.

Similarly, the much excess electricity from the SC engine is as a result of SC cycle generating more power due to much lower ambient temperature (below international standard atmosphere sea level static ISA SLS) of the region (site) over a year period, where majority of annual seasons ambient temperature falls below ISA SLS. On the other hand, IC and ICR would generate more power in a region of ambient temperature higher than ISA SLS.

The avoided or saved electricity and steam cost, grid electricity, and boiler heat cost, are the same in all three scenarios due to the constant (routine) consumption rate of the plant. Nevertheless, capital/installation cost was highest in the case of ICR LS-ADIGT-CHP, followed by IC LS-ADIGT-CHP, of course due to additional components and complexity (from intercooler, and recuperator). More so, highest GT fuel and emissions costs were incurred in the scenario of SC LS-ADIGT-CHP than the advanced cycles, due to lesser GT thermal efficiency and higher emission index of the former. Besides, it is pertinent to note that of all the annual cost elements, GT fuel cost contributes the largest share in all three CHP cases.

The increase in GT fuel, emissions, and O & M costs of SC LS-ADIGT-CHP outweighs the decrease in excess electricity and steam sales of IC LS-ADIGT-CHP and ICR LS-ADIGT-CHP. This explains why the advanced cycles show better NPV, IRR, and SPBP. Moreover, from the risk assessment, the probability of incurring loss in investment as defined by tendency of having negative mean NPV is lowest in the IC LS-ADIGT-CHP and highest in SC LS-ADIGT-CHP. This trend is the same in all three types of distributions studied.

Furthermore, it is observed that IRR of the LS-ADIGT-CHP cycle options increases as NPV increases, whereas SPBP decreases with increasing NPV, as shown in the combination of Figure 7-1, Figure 7-2, and Figure 7-3. More-so, the results of SPBP, and IRR obtained compare favourably with trends available in the literature. For instance, a 66MW CHP plant in the UK was reported to register an IRR of 12% and SPBP of 4.8 years (Merše et al, 2011).

7.3 Case study 2: small-scale ADIGT-CHP

The second case study is a small-scale Refinery plant CHP (SSRP-CHP) in the United Kingdom inspired by ConocoPhillips Whitegate Refinery CHP. The SSRP-CHP has an installed capacity of 6MW and **11.5** tonnes/hour of steam (RWE npower, 2013). This gives 547.515kW$_{th}$ of steam (because 1tonne/hour of steam = 47.61kW$_{th}$).

7.3.1 SS-ADIGT-CHP power plant performance module for SSRP

With the nominal capacity energy demand of the SSRP stated in section 7.3, 6 x 1.567MW SS-ADIGTs of which one is SS-ADIGT-CHP are considered to supply the demanded power and steam. This arrangement is made knowing that during hot days (in the summer) power generation on site may fall below demanded power. There may be surplus power and steam generated on site which are exported to the Grid. Conversely during plant outages electricity is imported from the Grid and steam produced in a stand-by boiler. The DP performance evaluation of the 1.567MW SS-ADIGT engine cycles using TURBOMATCH were shown in Table 4-1 while those of the 1.567MW SS-ADIGT-CHP cycles were shown in Table 5-1.

7.3.2 SS-ADIGT-CHP engines emissions module for SSRP

HEPHAESTUS code is deployed to estimate the engines emissions utilising dry low NO_x technology (DLN), and DP results were presented in Table 4-6. The total annual emissions of the ADIGT are computed based on the annual fuel consumptions, and the results are stated in Table 7-15, Table 7-17, and Table 7-19.

7.3.3 Economic analysis of SSRP ADIGT-CHP

To determine the economic viability of the SSRP ADIGT-CHP its profitability is measured against the conventional case of purchasing power from the Grid and employing an on-site boiler to generate steam. The method of economic evaluation used in section 7.2.3 is applied which include the criteria of NPV, SPBP, and IRR to compare investment in both simple (SC) and advanced cycles (RC and ICR) ADIGT-CHP.

The conventional case of purchasing grid power and producing steam in on-site boiler is firstly analysed followed by the analyses of SC, RC, and ICR SS-ADIGT-CHP cycles. Then the viabilities of the SS-ADIGT-CHP cycle options over the conventional case are compared.

7.3.3.1 Conventional case (grid power and on-site boiler) of SSRP

7.3.3.1.1 Energy demand of SSRP

The annual power and steam demand of the SSRP are computed based on the installed capacity stated in section 7.3 and are shown in Table 7-12. It is assumed that the refinery plant operates throughout the year.

Table 7-12 Energy demand of SSRP

Season	Days	Steam consumption demand (kWh_{th})	Power consumption demand (kWh_e)
Winter	37 Warm days	519044	5688000
	55 Cold days	712865	7812000
Spring	40 Hot days	545325	5976000
	50 Cold days	658113	7212000
Summer	43 Hot days	528352	5790000
	48 Cold days	647710	7098000
Autumn	38 Hot days	474696	5202000
	54 Cold days	710127	7782000
Annual total	365 days	4796231	52560000

Assumptions: the assumptions stated in section 7.2.3.1 are maintained in addition to those stated in section 6.4.2.1. Besides, two industrial boilers of 547.515kW$_{th}$ capacity each are proposed to be installed on site of which one would be kept on stand-by.

The capital cost and annual operation cost are computed as presented in Appendix D.3. The boiler capital cost is obtained as £87,602, while year (1) annual operation cost is found to be £5,524,589. The present value of year (1) annual operation cost is computed as £5,022,354. Loan is taken as £5,612,191, made of the sum of boiler capital cost and year (1) annual operation cost, whereas equal annual loan repayment is calculated to be £726,804 (see Appendix D.3). Two years loan holiday is allowed so that annual loan repayment would commence in year (3).

7.3.3.2 Conventional case life-cycle cash flow of SSRP CHP

Applying the escalation rates of prices (costs) to the life-cycle as stated in section 6.4.2.1, the life-cycle cash flow of the conventional case is computed and result is presented in Table 7-13.

Table 7-13 **Conventional case economic analysis of SSRP (Grid electricity + Boiler)**

			Electricity price £/kWh :		**0.1**	**interest rate(%):**	**5**
Boiler O & M cost £/kWh:		**0.004**	**Grid electricity /annum kWh :**		**52560000**	**Loan duration(yrs):**	**10**
Boiler capital cost £/kW:		**80**	**Hours of operation/annum:**		**8760**	**Loan (£):**	**5612191.36**
Boiler capital cost £:		**87602.4**	**Boiler gas fuel price £/kWh :**		**0.05**	**Repayment Holiday:**	**2 yrs**
emissions tax £ /kWh :		**0.002**	**10% Discount rate (d) :**		**0.1**		
End of year (t)	Boiler O & M cost, -$C_{o/m}$ (3% escalation rate) (£)	Grid electricity cost, -C_{Ge} (5% escalation rate) (£)	Boiler fuel cost, -C_{Bh} (5% escalation rate)(£)	Boiler emission cost - C_{bemtx} (3% escalation rate) (£)	Annual Loan repayment, C_{Lr} (£)	Annual cost (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	19185	5256000	239812	9592	0	5524589	5022354
2	19760	5518800	251802	9880	0	5800243	4793589
3	20353	5794740	264392	10177	726804	6816467	5121312
4	20964	6084477	277612	10482	726804	7120339	4863287
5	21593	6388701	291492	10796	726804	7439387	4619274
6	22241	6708136	306067	11120	726804	7774368	4388428
7	22908	7043543	321370	11454	726804	8126079	4169964
8	23595	7395720	337439	11798	726804	8495356	3963146
9	24303	7765506	354311	12151	726804	8883076	3767291
10	25032	8153781	372026	12516	726804	9290160	3581759
11	25783	8561470	390628	12891	726804	9717577	3405951
12	26556	8989544	410159	13278	726804	10166342	3239310
13	27353	9439021	430667	13677	0	9910718	2870782
14	28174	9910972	452200	14087	0	10405433	2740076
15	29019	10406520	474811	14509	0	10924859	2615324
16	29889	10926847	498551	14945	0	11470232	2496257
17	30786	11473189	523479	15393	0	12042847	2382613
18	31710	12046848	549653	15855	0	12644065	2274146
19	32661	12649191	577135	16331	0	13275317	2170620
20	33641	13281650	605992	16820	0	13938103	2071810
∑	**515506**	**173794655**	**7929598**	**257753**	**7268045**	**189765557**	**70557294**

7.3.3.3 SSRP ADIGT-CHP cases

The CHP economic analysis is implemented for both the simple and advanced cycle small-scale ADIGT-CHP, and results compared. The set of power plant was described in section 7.3.1. In addition to the assumptions stated in sections 6.4.2.1 and 7.2.3.1, it is assumed that one industrial boiler of 547.515kW$_{th}$ capacity is installed on site to be kept on stand-by and brought on stream during CHP outages.

7.3.3.3.1 Simple cycle (SC) SS-ADIGT-CHP case for SSRP

7.3.3.3.1.1 Energy generation and consumption for SC SS-ADIGT-CHP of SSRP

The annual power and steam demand of the SSRP were shown in Table 7-12. However, the three ADIGT-CHP cycle configurations generate different amounts of power and steam based on their respective features and prevailing climatic conditions of the site. The energy generation of the SC SS-ADIGT-CHP cycle is computed and is presented in Table 7-14. It is assumed that the power plant has an availability of about 95%.

Initial cash flow is the sum of installation costs of six 1.567MWe ADIGTs (of which one is fitted with a set of HRSG) and one 547.515kW$_{th}$ boiler. The initial cash flow which is the installation/capital cost and annual cash flow are computed by the method presented in Appendix D.4. The installation/capital cost is obtained as £9,445,801, while year (1) annual net cash flow is found to be £1,303,962. The present value of year (1) annual net cash flow is computed as £1,185,420. Loan is taken as £9,445,801 which is equal to the capital cost, whereas equal annual loan repayment is calculated to be £1,223,274 (see Appendix D.4). Two years loan holiday is allowed so that annual loan repayment would commence in year (3)

7.3.3.3.1.2 Simple cycle SS-ADIGT-CHP case life cycle cash flow for SSRP:

Applying the escalation rates of prices (costs) to the life-cycle as stated in section 6.4.2.1, the life-cycle cash flow of the simple cycle CHP case is computed and result is shown in Table 7-15.

Simple-payback-period (SPBP) is calculated by the method presented in Appendix D.4.1, and it is found to be 6.5 years. Similarly, NPV is calculated as shown in Appendix D.4.2 , and obtained as £2,895,053. More so, by method of iteration using Equation 6-7 the IRR for the SC SS-ADIGT-CHP case is determined to be 12.9%.

Table 7-14 Energy generation and consumption for SC SS-ADIGT-CHP of SSRP

Season	Days of power plant on stream	Average daily temp. (^oC)	Power consumption demand from power plant (kWh_e)	Power generated from 6 x 1.567MW GT (kWh_e)	Excess power exported to grid (kWh_e)	Grid electricity during plant outages (kWh_e)	Heat consumption demand from CHP (kWh_{th})	Heat generated from CHP (kWh_{th})	Excess heat exported (kWh_{th})	Boiler heat during CHP outages (kWh_{th})
Winter	36 Warm days	6	5460000	8930458	3470458	228000	498239	2764513	2266274	20806
	53 Cold days	0	7632000	13114524	5482524	180000	696439	3917709	3221270	16425
Spring	38 Hot days	10	5598000	8720620	3122620	378000	510831	2795498	2284666	34493
	48 Cold days	2	6912000	11877304	4965304	300000	630737	3548114	2917377	27376
Summer	39 Hot days	20	5340000	7501952	2161952	450000	487288	2589752	2102464	41064
	46 Cold days	10	6690000	10421749	3731749	408000	610479	3340815	2730336	37231
Autumn	35 Hot days	13	4878000	7598997	2720997	324000	445130	2435948	1990819	29566
	52 Cold days	6	7422000	12139535	4717535	360000	677276	3757915	3080639	32851
Annual total			49932000	80305139.13	30373139.1	2628000	4556419.8	25150263.4	20593843.5	239812

Table 7-15 Simple cycle (SC) SS-ADIGT-CHP case economic analysis of SSRP

				Boiler O&M cost £/kWh :	0.004	interest rate(%):	5
10% Discount rate (d) :	0.1	GT gas fuel price (£/kWh) :	0.05	Electricity tariff from grid £/kWhe	0.1	Loan duration(yrs):	10
GT-CHP capital cost £/kW:	1000	GT fuel consumed/annum (kg):	22154828	GT power consumed/annum (kWhe) :	49932000	Loan (£):	9445801.2
GT-CHP O&M var cost £/kWh:	0.01	Hours of CHP outages/annum:	438	Grid electricity /annum (kWhe) :	2628000	Repayment Holiday:	2 yrs
Initial cash flow (F_0) £:	9445801.2	Hours of CHP operation/annum:	8322	Boiler gas fuel price £/kWh$_{th}$	0.05		
	Excess electricity sold to Grid/annum(kWhe):		30373139	Steam export price £/kWh	0.025		
GT Emission tax £/kg :	0.005	Boiler capital cost £/kW$_{th}$:	80	Electricity export tariff to grid £/kWhe	0.05		
Boiler emission cost/annum £:	479.62314	Total emission/annum kg:	111502252	GT-CHP fixed O&M cost/annum £:	47010		

End of year (t)	O & M cost, $-C_{o/m}$ (3% escalation rate) (£)	GT fuel cost, $-C_f$ (5% escalation rate) (£)	Grid electricity cost, $-C_{Ge}$ (5% escalation rate) during outages of CHP (£)	Boiler heat cost, $-C_{Bh}$ (5% escalation rate) during outages of CHP (£)	Emission tax, $-C_{emtx}$ (3% escalation rate)(£)	Saved electricity cost , $+C_e$ (5% escalation rate) (£)	Saved heat cost , $+C_h$ (5% escalation rate) (£)	Revenue on excess electricity sold to Grid, $+R_e$ (5% escalation rate) (£)	Revenue on excess heat sold, $+R_h$ (5% escalation rate)(£)	Equal annual Loan repayment, $-C_{Lr}$ (£)	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	1102523	4015257	262800	11991	557991	4993200	227821	1518657	514846	0	1303962	1185420
2	1135599	4216020	275940	12590	574731	5242860	239212	1594590	540588	0	1402371	1158984
3	1169667	4426821	289737	13220	591973	5505003	251173	1674319	567618	1223274	283421	212939
4	1204757	4648162	304224	13881	609732	5780253	263731	1758035	595999	1223274	393989	269100
5	1240900	4880570	319435	14575	628024	6069266	276918	1845937	625799	1223274	511142	317379
6	1278127	5124598	335407	15303	646864	6372729	290764	1938234	657089	1223274	635241	358577
7	1316470	5380828	352177	16069	666270	6691366	305302	2035146	689943	1223274	766667	393421
8	1355965	5649870	369786	16872	686258	7025934	320567	2136903	724440	1223274	905819	422571
9	1396643	5932363	388275	17716	706846	7377231	336595	2243748	760662	1223274	1053118	446625
10	1438543	6228981	407689	18601	728052	7746092	353425	2355935	798695	1223274	1209007	466125
11	1481699	6540430	428074	19531	749893	8133397	371096	2473732	838630	1223274	1373953	481562
12	1526150	6867452	449477	20508	772390	8540066	389651	2597419	880562	1223274	1548446	493383
13	1571935	7210825	471951	21533	795562	8967070	409134	2727290	924590	0	2956278	856328
14	1619093	7571366	495549	22610	819428	9415423	429590	2863654	970819	0	3151442	829873
15	1667665	7949934	520326	23741	844011	9886194	451070	3006837	1019360	0	3357784	803827
16	1717695	8347431	546342	24928	869332	10380504	473623	3157179	1070328	0	3575907	778222
17	1769226	8764802	573659	26174	895412	10899529	497305	3315038	1123844	0	3806443	753084
18	1822303	9203042	602342	27483	922274	11444506	522170	3480790	1180037	0	4050058	728438
19	1876972	9663195	632460	28857	949942	12016731	548278	3654829	1239038	0	4307452	704303
20	1933281	10146354	664083	30300	978440	12617568	575692	3837570	1300990	0	4579363	680693
Σ	29625213	132768302	8689733	396480	14993424	165104922	7533118	50215841	17023877	12232745	41171862	12340854
Annual running cost of CHP (£)				=	3917059							
Present value of annual running cost of CHP (£)				=	3560962				NPV_{CHP} =	2895053		
Saving in CHP running cost over conventional running cost (£)=					1461391				IRR =	0.129	for NPV =	0.00
Simple payback period SPBP				=	6.5	Years						

7.3.3.3.2 Recuperated cycle (RC) SS-ADIGT-CHP case for SSRP

7.3.3.3.2.1 Energy generation and consumption for RC SS-ADIGT-CHP of SSRP

Following same reasons and assumption in section 7.3.3.3.1.1, the energy generation of the RC SS-ADIGT-CHP cycle is computed and is shown in Table 7-16.

Assuming 0.5% increment in GT capital cost due to recuperator, and applying same method of Appendix D.4 as stated in section 7.3.3.3.1.1, the installation/capital cost for RC SS-ADIGT-CHP is calculated as £9,492,811, which is equal to the loan taken. Equal annual loan repayment, C_{Lr} is calculated as £1,229,362 and repayment would commence in year (3).

7.3.3.3.2.2 Year 1 annual net cash flow for RC SS-ADIGT-CHP case of SSRP:

Using the same method of Appendix D.4

$C_{o/m} = £1128638$; $\mathrm{C_f} = £4031066$; $\mathrm{C_{Ge}} = £262800$;
$\mathrm{C_{Bh}} = £11991$; $\mathrm{C_{emtx}} = £489163$; $\mathrm{C_e} = £4993200$

$\mathrm{C_h} = £227821$; $\mathrm{R_e} = £1534466$; $\mathrm{R_h} = £572228$

Year 1 annual net cash flow, $\mathrm{F_1} = £1{,}404{,}058$, and its present value is £1,276,416

7.3.3.3.2.3 RC SS-ADIGT-CHP case life cycle cash flow for SSRP:

Applying the escalation rates of prices (costs) to the life-cycle as stated in section 6.4.2.1, the life-cycle cash flow of the RC ADIGT-CHP case is computed and result is shown in Table 7-17.

As shown in Appendix D.4.3, simple-payback-period (SPBP) is calculated as 6.1 years. Similarly, NPV is found to be £3,958,516 as shown in Appendix D.4.4. More so, by method of iteration using Equation 6-7 the internal rate of return (IRR) for the RC SS-ADIGT-CHP case is determined to be 13.9%.

Table 7-16 Energy generation and consumption for RC SS-ADIGT-CHP of SSRP

Season	Days of power plant on stream	Average daily temp. (^oC)	Power consumption demand from power plant (kWh_e)	Power generated from 6 x 1.567MW GT (kWh_e)	Excess power exported to grid (kWh_e)	Grid electricity during plant outages (kWh_e)	Heat consumption demand from CHP (kWh_{th})	Heat generated from CHP (kWh_{th})	Excess heat exported (kWh_{th})	Boiler heat during CHP outages (kWh_{th})
Winter	36 Warm days	6	5460000	8969879	3509879	228000	498239	3017709	2519471	20806
	53 Cold days	0	7632000	13197178	5565178	180000	696439	4279783	3583343	16425
Spring	38 Hot days	10	5598000	8744020	3146020	378000	510831	3049161	2538329	34493
	48 Cold days	2	6912000	11952161	5040161	300000	630737	3876029	3245292	27376
Summer	39 Hot days	20	5340000	7495865	2155865	450000	487288	2819833	2332545	41064
	46 Cold days	10	6690000	10449713	3759713	408000	610479	3643959	3033480	37231
Autumn	35 Hot days	13	4878000	7619387	2741387	324000	445130	2656986	2211856	29566
	52 Cold days	6	7422000	12193121	4771121	360000	677276	4102095	3424819	32851
Annual total			49932000	80621324.97	30689325	2628000	4556419.83	27445555	22889135	239812

Table 7-17 Recuperated cycle (RC) SS-ADIGT-CHP case economic analysis of SSRP

				Boiler O&M cost £/kWh :	0.004	interest rate(%):	5	
10% Discount rate (d) :	0.1	GT gas fuel price (£/kWh) :	0.05	Electricity tariff from grid £/kWhe :	0.1	Loan duration(yrs):	10	
GT-CHP capital cost £/kW:	1005	GT fuel consumed/annum (kg) :	19426144	Electricity consumed/annum (kWhe) :	49932000	Loan (£):	9492811.2	
GT-CHP O&M var cost £/kWh:	0.01	Hours of CHP outages/annum:	438	Grid electricity /annum (kWhe) :	2628000	Repayment Holiday:	2 yrs	
Initial cash flow (F_0) £:	9492811.2	Hours of CHP operation/annum:	8322	Boiler gas fuel price £/kWht :	0.05			
		Excess electricity sold to Grid/annum(kWhe):	30689325	Steam export price £/kWh :	0.025			8270551.2
Emission tax £/kg :	0.005	Boiler capital cost £/kWt :	80	Electricity export tariff to grid £/kWhe :	0.05			
Boiler emission cost/annum £:	479.62314	Total emission/annum kg:	97736725	GT-CHP fixed O&M cost/annum £:	47010			

End of year (t)	O & M cost, $-C_{o/m}$ (3% escalation rate) (£)	GT fuel cost, $-C_f$ (5% escalation rate) (£)	Grid electricity cost, $-C_{Ge}$ (5% escalation rate) during outages of CHP (£)	Boiler heat cost, $-C_{Bh}$ (5% escalation rate) during outages of CHP (£)	Emission tax, $-C_{emtx}$ (3% escalation rate)(£)	Saved electricity cost, $+C_e$ (5% escalation rate) (£)	Saved heat cost, $+C_h$ (5% escalation rate) (£)	Revenue on excess electricity sold to Grid, $+R_e$ (5% escalation rate) (£)	Revenue on excess heat sold, $+R_h$ (5% escalation rate)(£)	Annual Loan repayment, - CLr (£)	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	1128638	4031066	262800	11991	489163	4993200	227821	1534466	572228	0	1404058	1276416
2	1162497	4232620	275940	12590	503838	5242860	239212	1611190	600840	0	1506616	1245138
3	1197372	4444251	289737	13220	518953	5505003	251173	1691749	630882	1229362	385911	289941
4	1233293	4666463	304224	13881	534522	5780253	263731	1776336	662426	1229362	501002	342191
5	1270292	4899786	319435	14575	550558	6069266	276918	1865153	695547	1229362	622876	386757
6	1308401	5144776	335407	15303	567074	6372729	290764	1958411	730325	1229362	751905	424431
7	1347653	5402014	352177	16069	584086	6691366	305302	2056332	766841	1229362	888478	455930
8	1388082	5672115	369786	16872	601609	7025934	320567	2159148	805183	1229362	1033005	481904
9	1429725	5955721	388275	17716	619657	7377231	336595	2267106	845442	1229362	1185917	502945
10	1472617	6253507	407689	18601	638247	7746092	353425	2380461	887714	1229362	1347669	519585
11	1516795	6566182	428074	19531	657394	8133397	371096	2499484	932100	1229362	1518737	532308
12	1562299	6894491	449477	20508	677116	8540066	389651	2624458	978705	1229362	1699626	541553
13	1609168	7239216	471951	21533	697430	8967070	409134	2755681	1027640	0	3120226	903818
14	1657443	7601177	495549	22610	718353	9415423	429590	2893465	1079022	0	3322370	874884
15	1707166	7981235	520326	23741	739903	9886194	451070	3038138	1132973	0	3536004	846491
16	1758381	8380297	546342	24928	762100	10380504	473623	3190045	1189622	0	3761746	818665
17	1811133	8799312	573659	26174	784963	10899529	497305	3349547	1249103	0	4000243	791427
18	1865467	9239278	602342	27483	808512	11444506	522170	3517025	1311558	0	4252177	764791
19	1921431	9701242	632460	28857	832768	12016731	548278	3692876	1377136	0	4518265	738772
20	1979074	10186304	664083	30300	857751	12617568	575692	3877520	1445993	0	4799262	713380
$\sum$	30326927	133291052	8689733	396480	13144000	165104922	7533118	50738591	18921277	12293625	44156093	13451327
Annual running cost of CHP (£)				=	3816963							
Present value of annual running cost of CHP (£)				=	3469967				NPV_{CHP} =	3958516		
Saving in CHP running cost over conventional running cost (£)=					1552387				IRR =	0.139	for NPV =	0.00
Simple payback period SPBP				=	6.1	Years						

7.3.3.3.3 Intercooled/recuperated cycle ICR SS-ADIGT-CHP case for SSRP

7.3.3.3.3.1 Energy generation and consumption for ICR SS-ADIGT-CHP of SSRP

Following same reasons and assumption in section 7.3.3.3.1.1, the energy generation of the ICR SS-ADIGT-CHP cycle is computed and is shown in Table 7-18

Assuming 1.0% increment in GT capital cost due to intercooler and recuperator, and applying same method of Appendix D.4 as stated in section 7.3.3.3.1.1, the installation/capital cost for ICR SS-ADIGT-CHP is calculated as £9,539,821, which is equal to the loan taken. Equal annual loan repayment, C_{Lr} is found to be £1,235,450 and repayment would commence in year (3).

7.3.3.3.3.2 Year 1 annual net cash flow for ICR SS-ADIGT-CHP case of SSRP:

Applying the same method of Appendix D.4

$C_{o/m} = £1055539$; $\mathrm{C_f} = £3914989$; $\mathrm{C_{Ge}} = £262800$

$\mathrm{C_{Bh}} = £11991$; $\mathrm{C_{emtx}} = £486108$; $\mathrm{C_e} = £4993200$

$\mathrm{C_h} = £227821$; $\mathrm{R_e} = £1418389$; $\mathrm{R_h} = £447520$

Year 1 annual net cash flow, $\mathrm{F_1} = £1355503$, having its present value as £1,232,276

7.3.3.3.3.3 ICR SS-ADIGT-CHP case life cycle cash flow for SSRP:

Applying the escalation rates of prices (costs) to the life-cycle as stated in section 6.4.2.1, the life-cycle cash flow of the ICR ADIGT-CHP case is computed and result is presented in Table 7-19 .

Simple-payback-period (SPBP) is calculated as shown in Appendix D.4.5, and it is found to be 6.3 years. Similarly, NPV is calculated to be £3,165,958 as shown in Appendix D.4.6. More so, by method of iteration using Equation 6-7 the IRR for the ICR SS-ADIGT-CHP case is determined to be 13.1%.

Figure 7-32, Figure 7-33, and Figure 7-34 show the comparison between the NPV, SPBP, and IRR of the simple, intercooled, and ICR cycle SS-ADIGT-CHP for the SSRP. The percentage savings in operational cost of the three SRP CHP cases over the conventional case is presented in Figure 7-35.

Table 7-18 Energy generation and consumption for ICR SS-ADIGT-CHP of SSRP

Season	Days of power plant on stream	Average daily temp. (^oC)	Power consumption demand from power plant (kWh_e)	Power generated from 6 x 1.567MW GT (kWh_e)	Excess power exported to grid (kWh_e)	Grid electricity during plant outages (kWh_e)	Heat consumption demand from CHP (kWh_{th})	Heat generated from CHP (kWh_{th})	Excess heat exported (kWh_{th})	Boiler heat during CHP outages (kWh_{th})
Winter	36 Warm days	6	5460000	8662290	3202290	228000	498239	2463394	1965156	20806
	53 Cold days	0	7632000	12517816	4885816	180000	696439	3472769	2776330	16425
Spring	38 Hot days	10	5598000	8593518	2995518	378000	510831	2504534	1993703	34493
	48 Cold days	2	6912000	11336890	4424890	300000	630737	3145150	2514412	27376
Summer	39 Hot days	20	5340000	7656172	2316172	450000	487288	2347278	1859990	41064
	46 Cold days	10	6690000	10269852	3579852	408000	610479	2993093	2382614	37231
Autumn	35 Hot days	13	4878000	7488242	2610242	324000	445130	2182408	1737278	29566
	52 Cold days	6	7422000	11775003	4353003	360000	677276	3348592	2671316	32851
Annual total			49932000	78299782	28367782	2628000	4556419.83	22457219	17900799	239812

Table 7-19 Intercooled-recuperated cycle (ICR) SS-ADIGT-CHP case economic analysis of SSRP

						Boiler O&M cost £/kWh :			**0.004**	**interest rate(%):**	**5**	
10% Discount rate (d) :		**0.1**	**GT gas fuel price (£/kWh) :**		**0.05**	**Electricity tariff from grid £/kWhe**			**0.1**	**Loan duration(yrs):**	**10**	
GT-CHP capital cost £/kW:		**1010**	**GT fuel consumed/annum (kg):**		**19291328**	**Electricity consumed/annum (kWhe):**			**49932000**	**Loan (£)**	**9539821.2**	
GT-CHP O&M var cost £/kWh:		**0.01**	**Hours of CHP outages/annum:**		**438**	**Grid electricity /annum (kWhe)**			**2628000**	**Repayment Holiday:**	**2 yrs**	
Initial cash flow (F_0) £:		**9539821.2**	**Hours of CHP operation/annum:**		**8322**	**Boiler gas fuel price £/kWht**			**0.05**			
		Excess electricity sold to Grid/annum(kWhe):			**28367782**	**Steam export price £/kWh :**			**0.025**			
Emission tax £/kg :		**0.005**	**Boiler capital cost £/kWt :**		**80**	**Electricity export tariff to grid £/kWhe:**			**0.05**			
Boiler emission cost/annum £:		**479.62314**	**Total emission/annum kg:**		**97125664**	**GT-CHP fixed O&M cost/annum £:**			**47010**			
End of year (t)	O & M cost, $-C_{o/m}$ (3% escalation rate) (£)	GT fuel cost, $-C_f$ (5% escalation rate) (£)	Grid electricity cost, $-C_{Ge}$ (5% escalation rate) during outages of CHP (£)	Boiler heat cost, $-C_{Bh}$ (5% escalation rate) during outages of CHP (£)	Emission tax, $-C_{emtx}$ (3% escalation rate)(£)	Saved electricity cost, $+C_e$ (5% escalation rate) (£)	Saved heat cost, $+C_h$ (5% escalation rate) (£)	Revenue on excess electricity sold to Grid, $+R_e$ (5% escalation rate) (£)	Revenue on excess heat sold, $+R_h$ (5% escalation rate)(£)	Annual Loan repayment, $-CLr$ (£)	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	1055539	3914989	262800	11991	486108	4993200	227821	1418389	447520	0	1355503	1232276
2	1087205	4110739	275940	12590	500691	5242860	239212	1489309	469896	0	1454111	1201745
3	1119822	4316275	289737	13220	515712	5505003	251173	1563774	493391	1235450	323124	242768
4	1153416	4532089	304224	13881	531183	5780253	263731	1641963	518060	1235450	433764	296266
5	1188019	4758694	319435	14575	547119	6069266	276918	1724061	543963	1235450	550916	342076
6	1223659	4996628	335407	15303	563532	6372729	290764	1810264	571161	1235450	674937	380985
7	1260369	5246460	352177	16069	580438	6691366	305302	1900777	599720	1235450	806201	413708
8	1298180	5508783	369786	16872	597851	7025934	320567	1995816	629706	1235450	945099	440896
9	1337126	5784222	388275	17716	615787	7377231	336595	2095607	661191	1235450	1092048	463135
10	1377239	6073433	407689	18601	634261	7746092	353425	2200387	694250	1235450	1247481	480958
11	1418556	6377105	428074	19531	653288	8133397	371096	2310406	728963	1235450	1411857	494847
12	1461113	6695960	449477	20508	672887	8540066	389651	2425927	765411	1235450	1585660	505240
13	1504947	7030758	471951	21533	693074	8967070	409134	2547223	803682	0	3004846	870397
14	1550095	7382296	495549	22610	713866	9415423	429590	2674584	843866	0	3199048	842409
15	1596598	7751411	520326	23741	735282	9886194	451070	2808313	886059	0	3404280	814958
16	1644496	8138981	546342	24928	757340	10380504	473623	2948729	930362	0	3621131	788064
17	1693831	8545930	573659	26174	780061	10899529	497305	3096166	976880	0	3850225	761746
18	1744646	8973227	602342	27483	803462	11444506	522170	3250974	1025724	0	4092214	736021
19	1796985	9421888	632460	28857	827566	12016731	548278	3413523	1077010	0	4347787	710898
20	1850894	9892983	664083	30300	852393	12617568	575692	3584199	1130861	0	4617667	686387
Σ	**28362735**	**129452850**	**8689733**	**396480**	**13061903**	**165104922**	**7533118**	**46900389**	**14797675**	**12354505**	**42017899**	**12705779**
Annual running cost of CHP (£) =					**3865518**							
Present value of annual running cost of CHP (£) =					**3514107**				**NPV_{CHP} =**	**3165958**		
Saving in CHP running cost over conventional running cost (£) =					**1508247**				**IRR =**	**0.131**	**for NPV =**	**0.00**
Simple payback period SPBP =					**6.3**	**Years**						

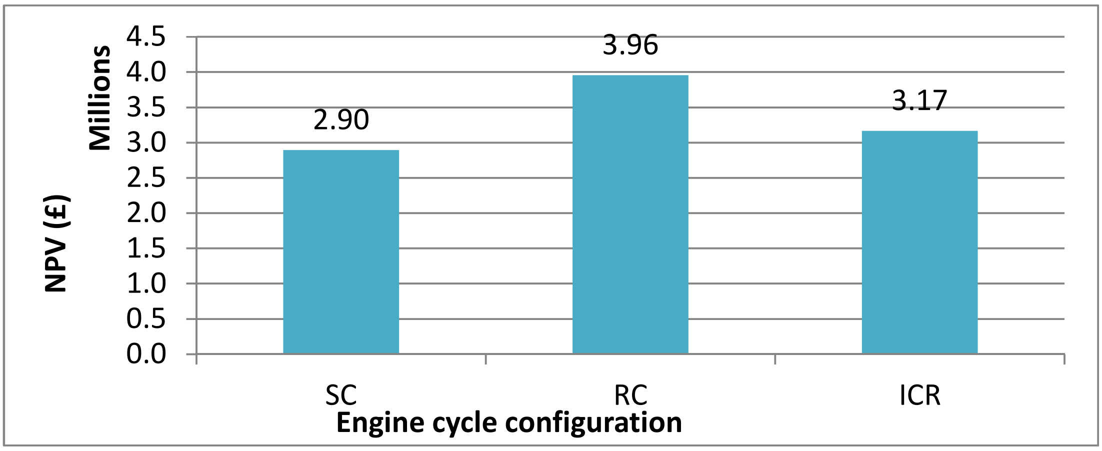


Figure 7-32 Net present value for SSRP ADIGT-CHP

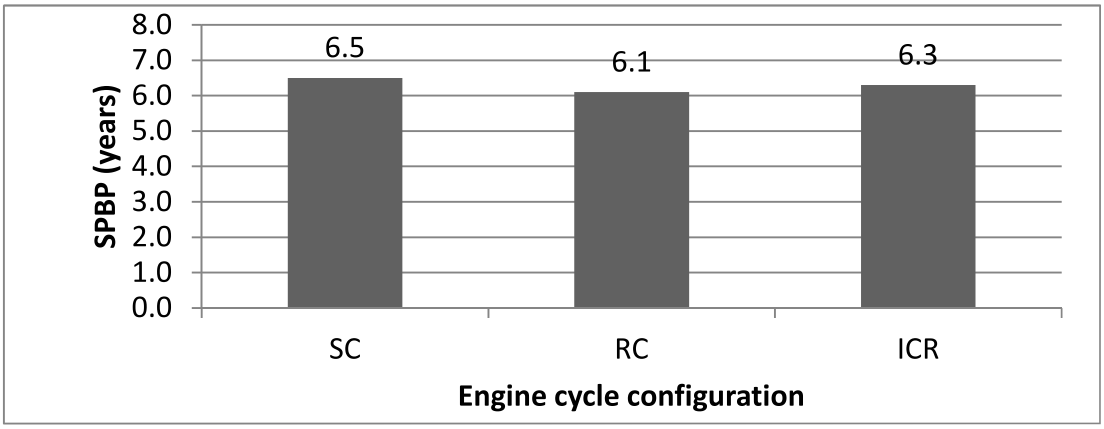


Figure 7-33 Simple payback period for SSRP ADIGT-CHP

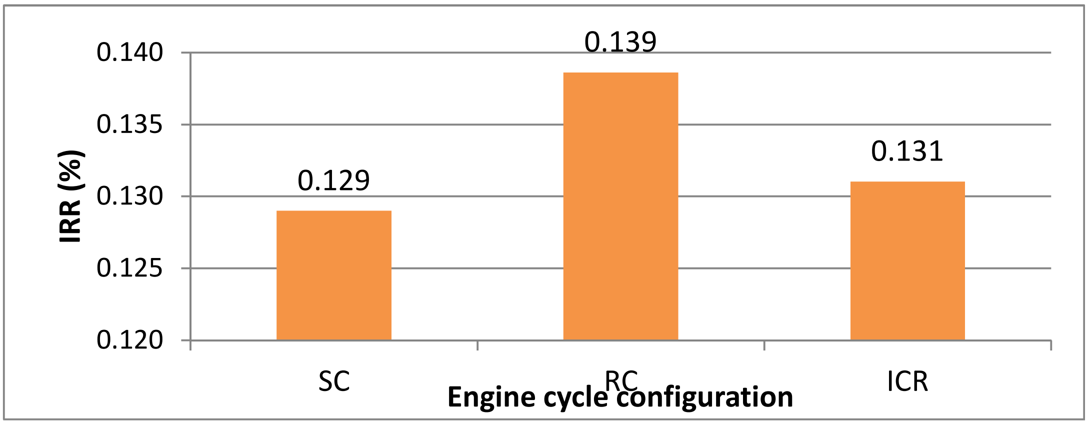


Figure 7-34 IRR for SSRP ADIGT-CHP

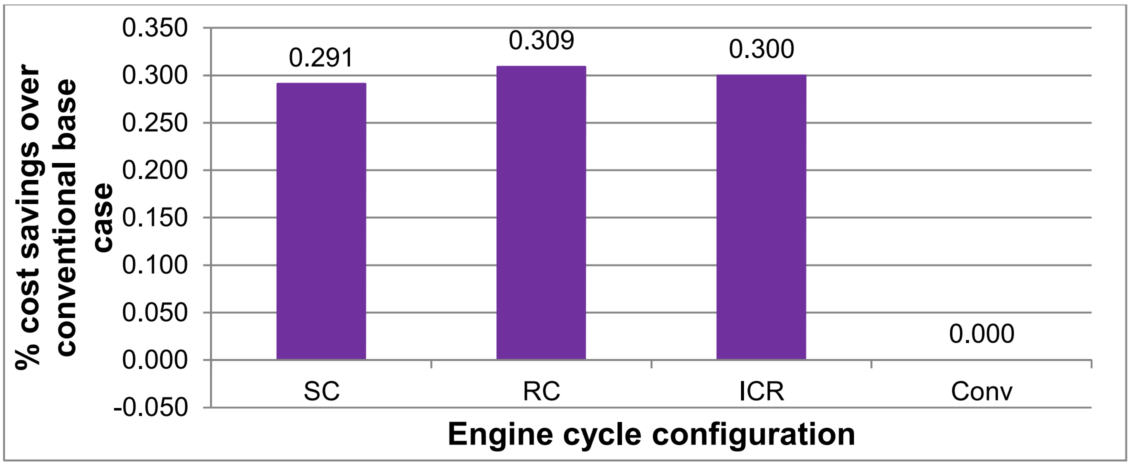


Figure 7-35 Percentage cost savings of SSRP ADIGT-CHP over conventional case

7.3.4 Risk analysis of SSRP ADIGT-CHP

Risk assessment of the SSRP ADIGT-CHP is accomplished by integrating the software @Risk 6.0 to perform Latin Hypercube sampling (a modified Monte Carlo simulation) of 10,000 random number generations of values of some inputs to determine their probability effects on NPV.

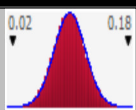
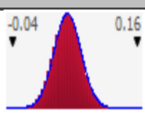
7.3.4.1 Probability distributions of inputs for SSRP CHP

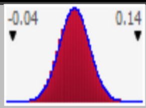
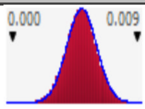
Grid electricity price, gas turbine gas fuel price, electricity export price, and emission tax, are identified as economic inputs of high uncertainty. So their probability effects on NPV are simulated for the three various engine cycles. Three types of probability distributions are studied, namely, normal, triangular, and uniform, distributions.

7.3.4.1.1 Normal distribution of inputs for SSRP CHP

Normal frequency distributions are defined for the inputs as presented in Table 7-20.

Table 7-20 Normal distribution of inputs defined for SSRP CHP

Inputs	Normal graph	standard deviation (σ)	Minimum	Mean	Maximum	5th percentile	95th percentile
Electricity tariff from grid £/kWhe:		0.02	0.026	0.1	0.178	0.067	0.133
Electricity export tariff to grid £/kWhe :		0.02	-0.028	0.05	0.147	0.017	0.083

Inputs	Normal graph	standard deviation (σ)	Minimum	Mean	Maximum	5th percentile	95th percentile
GT gas fuel price (£/kWh):		0.02	-0.025	0.05	0.132	0.017	0.083
Emission tax £/kg :		0.001	0.001	0.005	0.009	0.003	0.007

These inputs distributions are maintained in the risk simulation for the SC, IC, and ICR cycles ADIGT-CHP of SRP.

7.3.4.1.2 Results of normal distribution risk analysis of SSRP ADIGT-CHP

The results of probability distributions of NPV for the three cycles are as presented in Figure 7-36 to Figure 7-38. Besides, the results of sensitivity of NPV to variations in values of inputs are shown in Figure 7-39 to Figure 7-41, whereas the ranking of inputs by their effects on NPV is shown in Figure 7-42 to Figure 7-44.

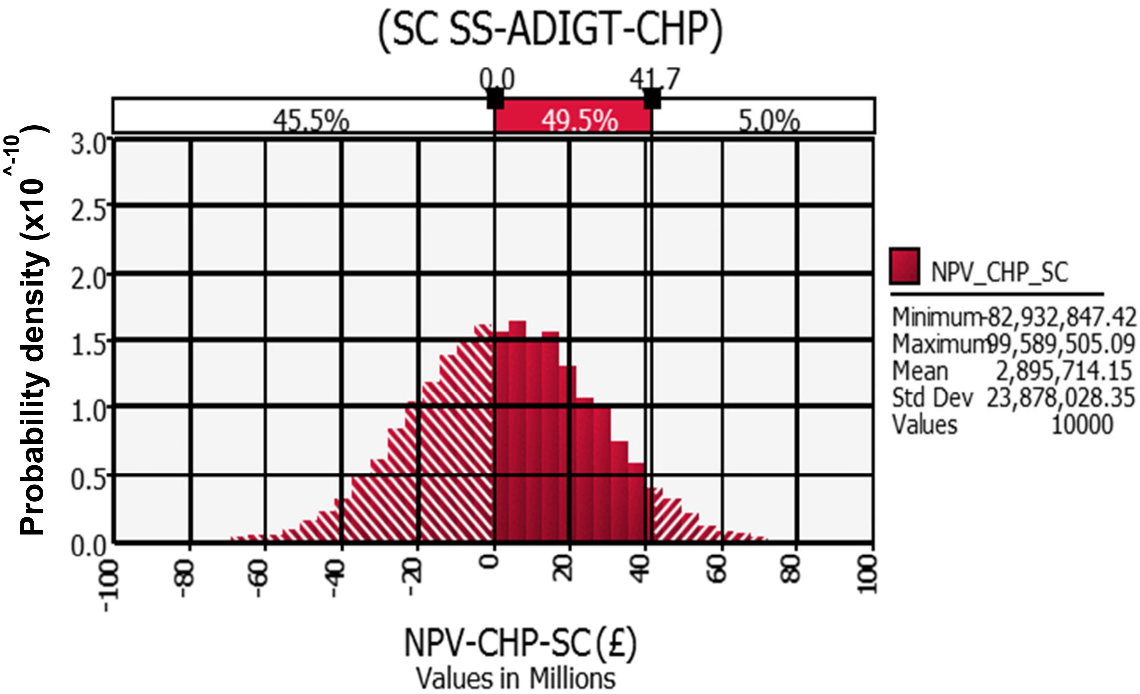


Figure 7-36 Normal probability distribution of NPV for SC SS-ADIGT-CHP of SSRP

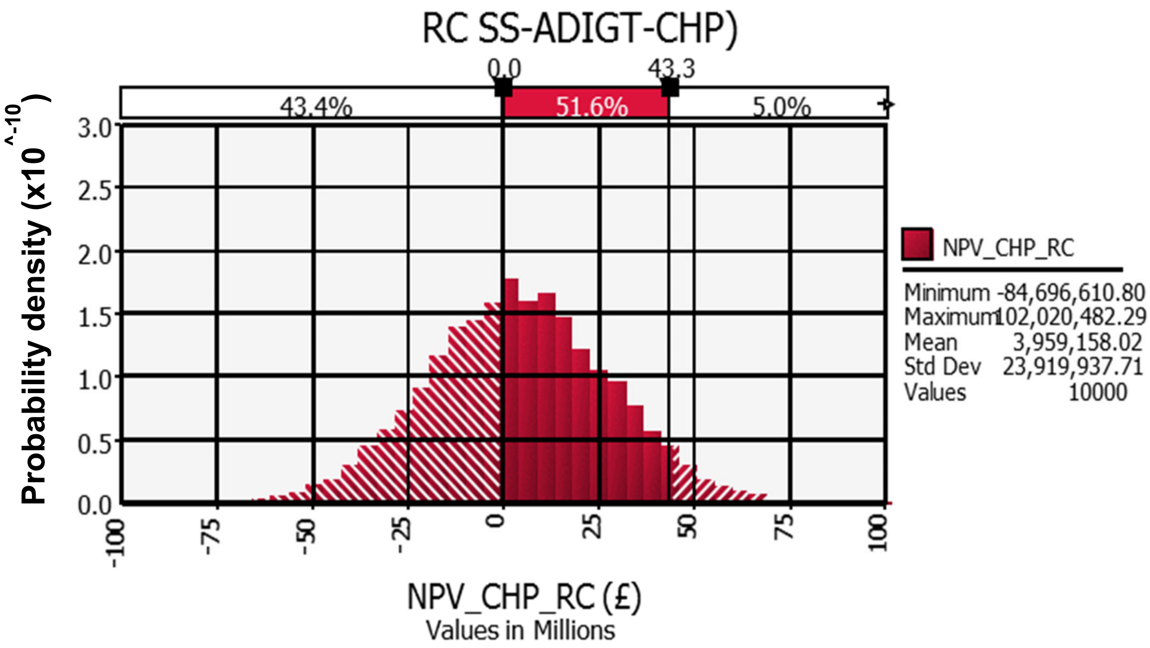


Figure 7-37 Normal probability distribution of NPV for RC SS-ADIGT-CHP of SSRP

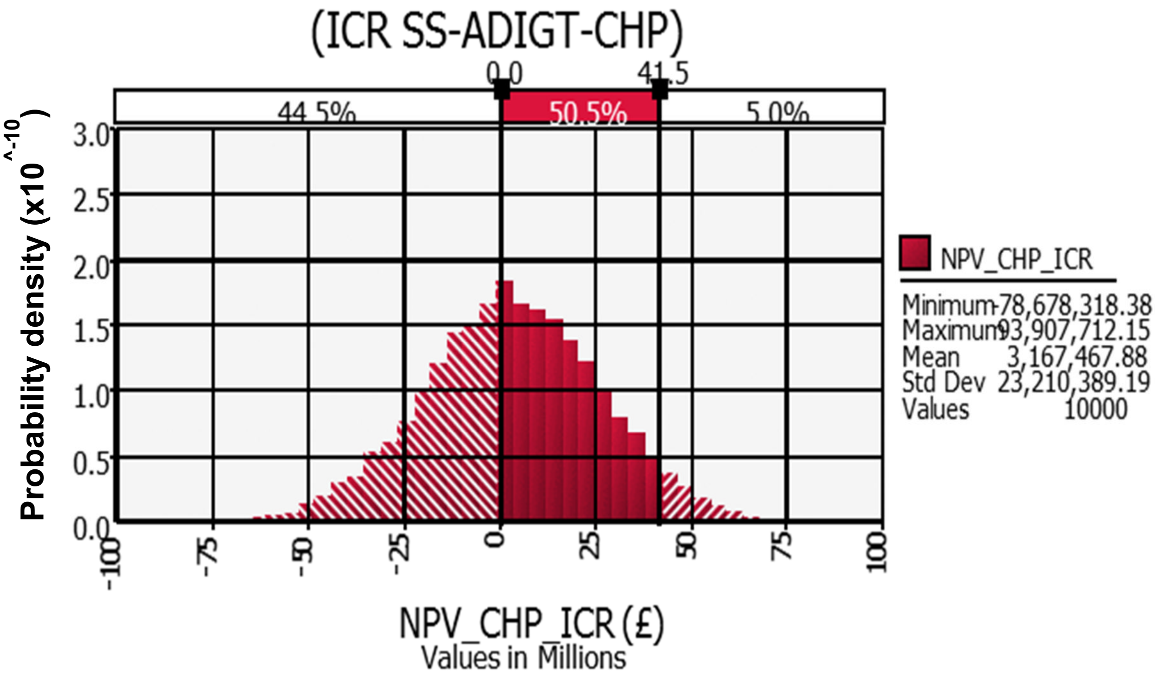


Figure 7-38 Normal probability distribution of NPV for ICR SS-ADIGT-CHP of SSRP

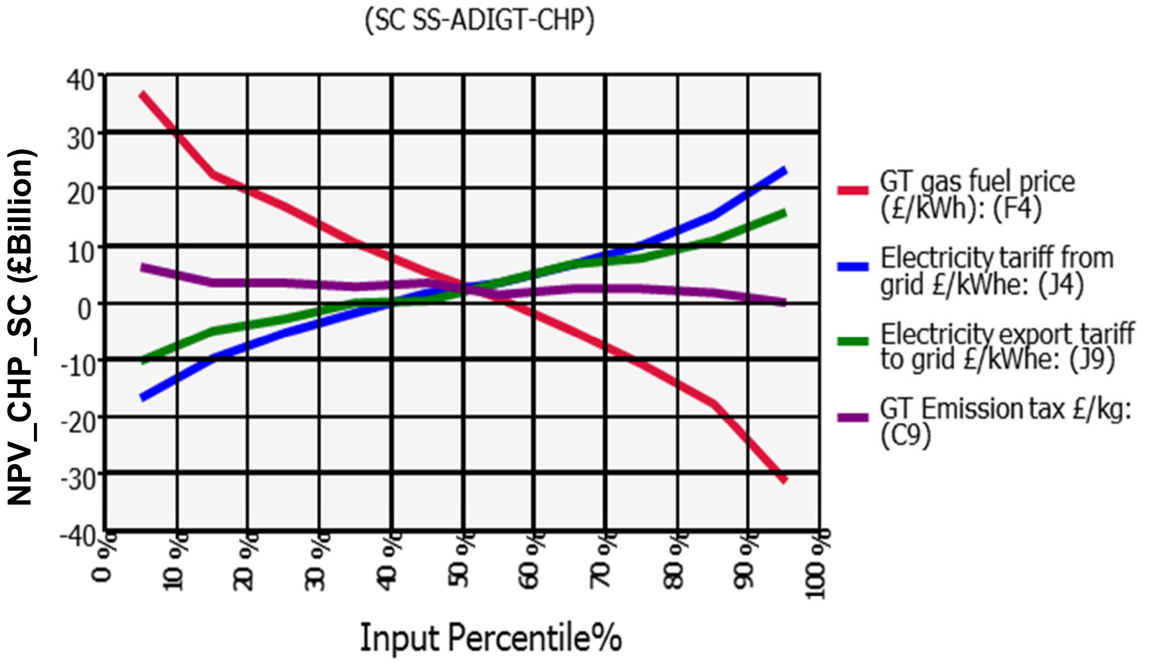


Figure 7-39 Sensitivity of NPV to changes in inputs values for SC SS-ADIGT-CHP of SSRP (Normal distribution)

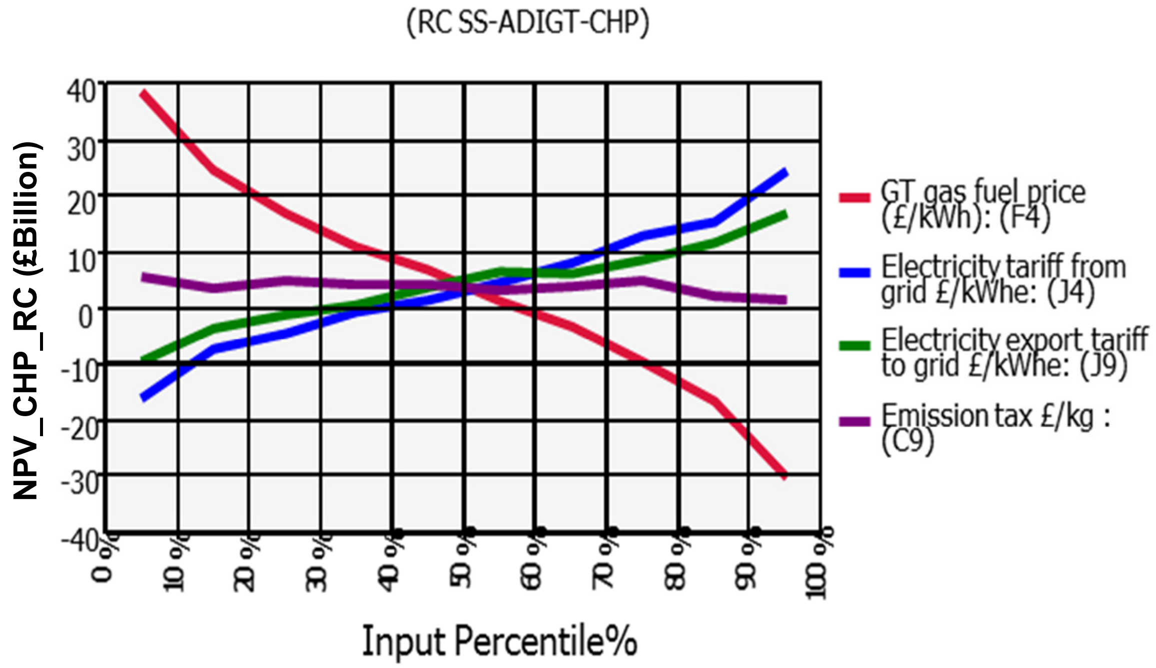


Figure 7-40 Sensitivity of NPV to changes in inputs values for RC SS-ADIGT-CHP of SSRP (Normal distribution)

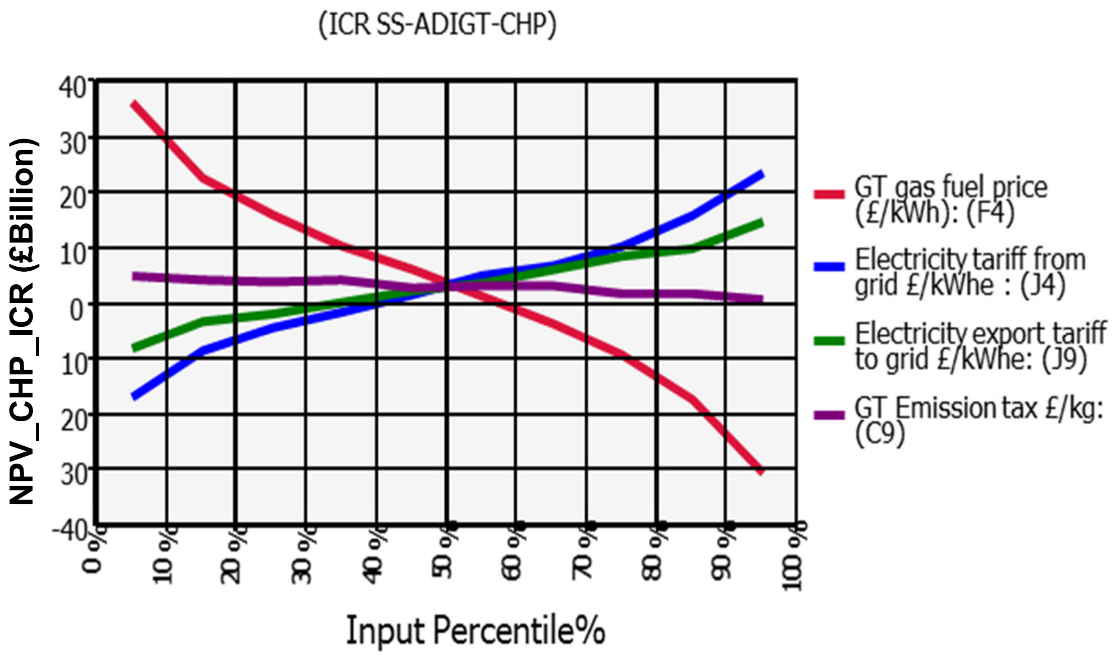


Figure 7-41 Sensitivity of NPV to changes in inputs values for ICR SS-ADIGT-CHP of SSRP (Normal distribution)

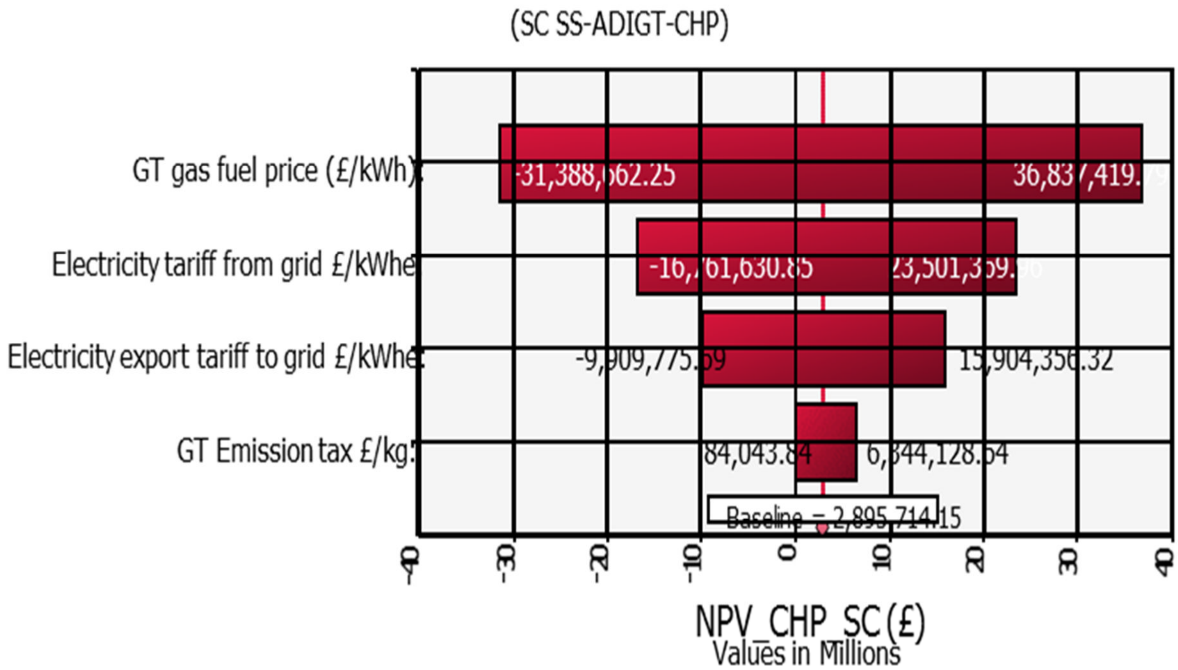


Figure 7-42 Inputs ranked by effects on NPV for SC SS-ADIGT-CHP of SSRP (Normal distribution)

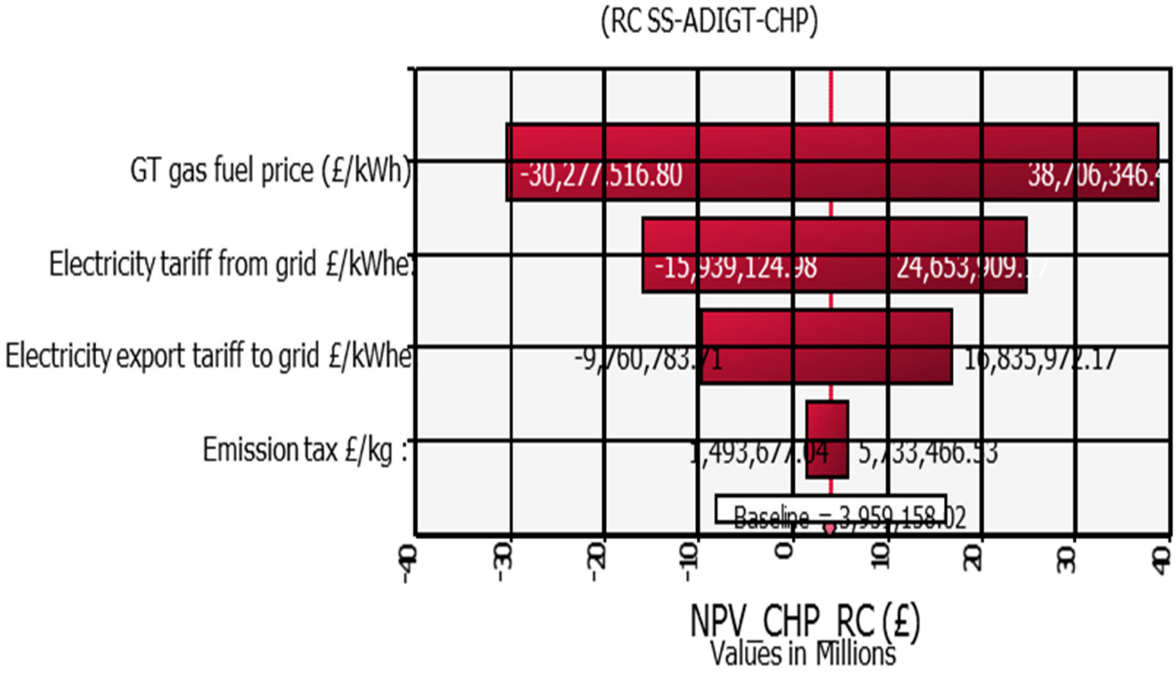


Figure 7-43 Inputs ranked by effects on NPV for RC SS-ADIGT-CHP of SSRP (Normal distribution)

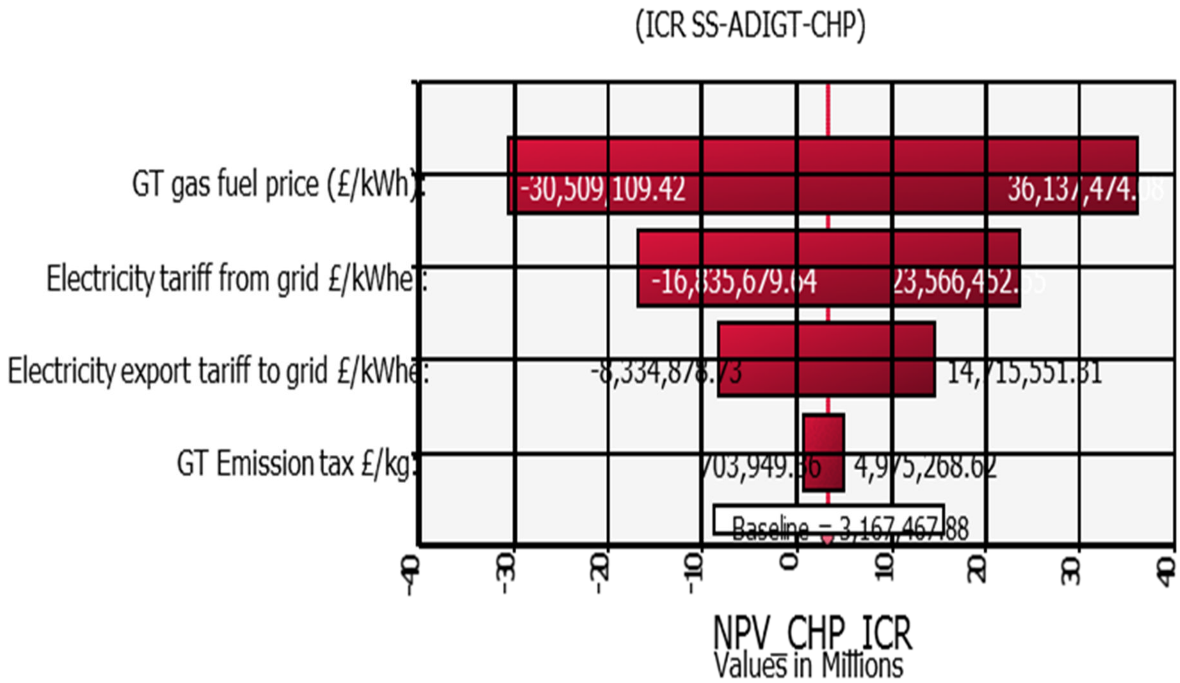


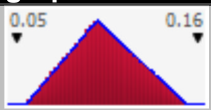
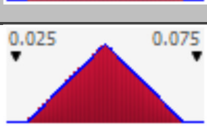
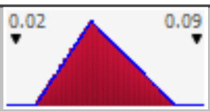
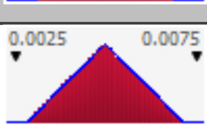
Figure 7-44 Inputs ranked by effects on NPV for ICR SS-ADIGT-CHP of SSRP (Normal distribution)

From the normal distribution results the probability of having less than zero or zero NPV which is the range for making loss in investment is obtained as 45.5% for SC, 43.4% for RC, and 44.5% for ICR as presented in Figure 7-36 to Figure 7-38. It is important to state that the idea here is not about pegging the design for low probability, instead the aim of the analysis is to formulate a procedure or method of assessment and comparing performance of engine cycles.

7.3.4.1.3 Triangular distribution of inputs for SSRP CHP

Triangular frequency distributions are defined for the inputs as presented in Table 7-21 .

Table 7-21 Triangular distribution of inputs defined for SSRP CHP.

Inputs	Triangular graph	Minimum	Mean	Maximum	5th percentile	95th percentile
Electricity tariff from grid £/kWhe:		0.06	0.1	0.15	0.073	0.135
Electricity export tariff to grid £/kWhe :		0.03	0.05	0.07	0.036	0.064
GT gas fuel price (£/kWh):		0.03	0.05	0.08	0.037	0.071
Emission tax £/kg :		0.003	0.005	0.007	0.0036	0.0064

7.3.4.1.4 Results of triangular distribution risk analysis for SSRP CHP

Following the same procedure of section 7.3.4.1.1, the results of triangular probability distributions of NPV for the three cycles are as presented in Figure 7-45 to Figure 7-47. Besides, the results of sensitivity of NPV to variations in values of inputs are shown in Figure 7-48 to Figure 7-50, whereas the rankings of inputs by their effects on NPV are shown in Figure 7-51 to Figure 7-53.

From the triangular distribution results the probability of having less than zero or zero NPV which is the range for making loss in investment is obtained as 45.6% for SC, 42.8% for RC, and 45.2% for ICR as shown in Figure 7-45 to Figure 7-47.

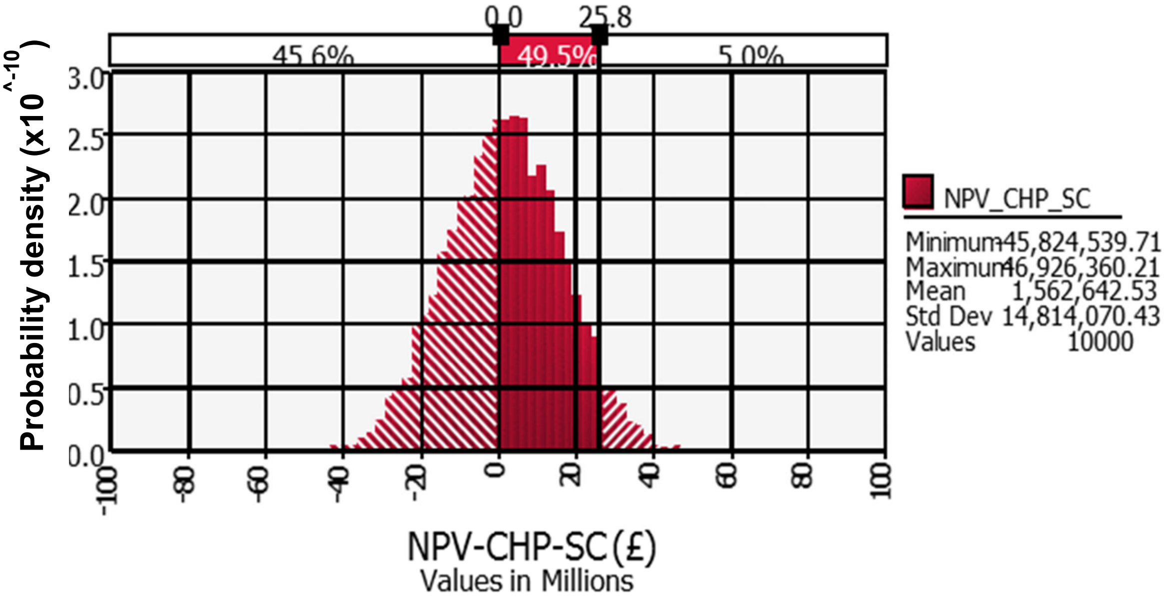


Figure 7-45 Triangular probability distribution of NPV for SC SS-ADIGT-CHP of SSRP

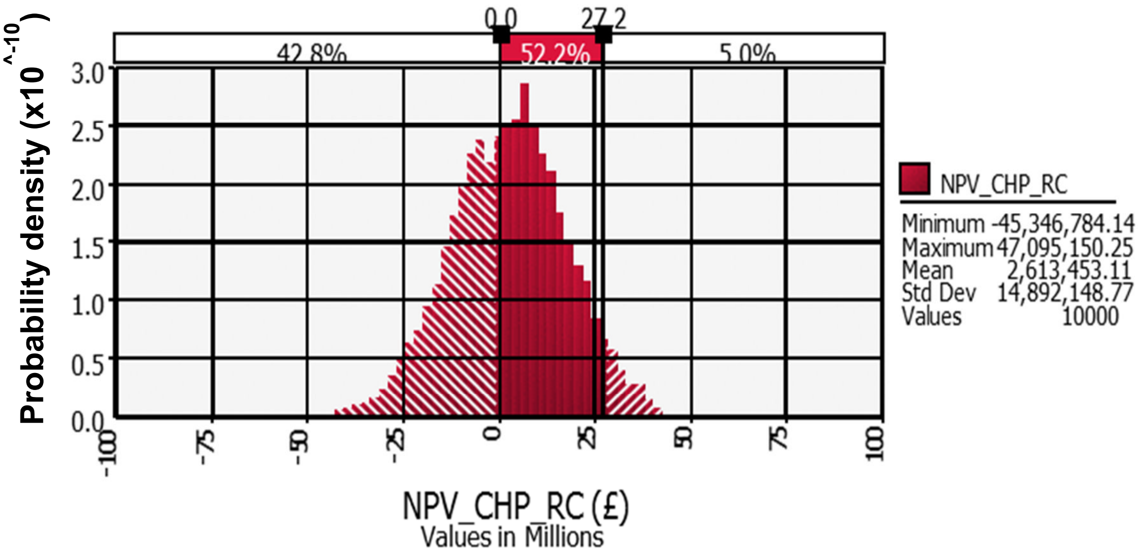


Figure 7-46 Triangular probability distribution of NPV for RC SS-ADIGT-CHP of SSRP

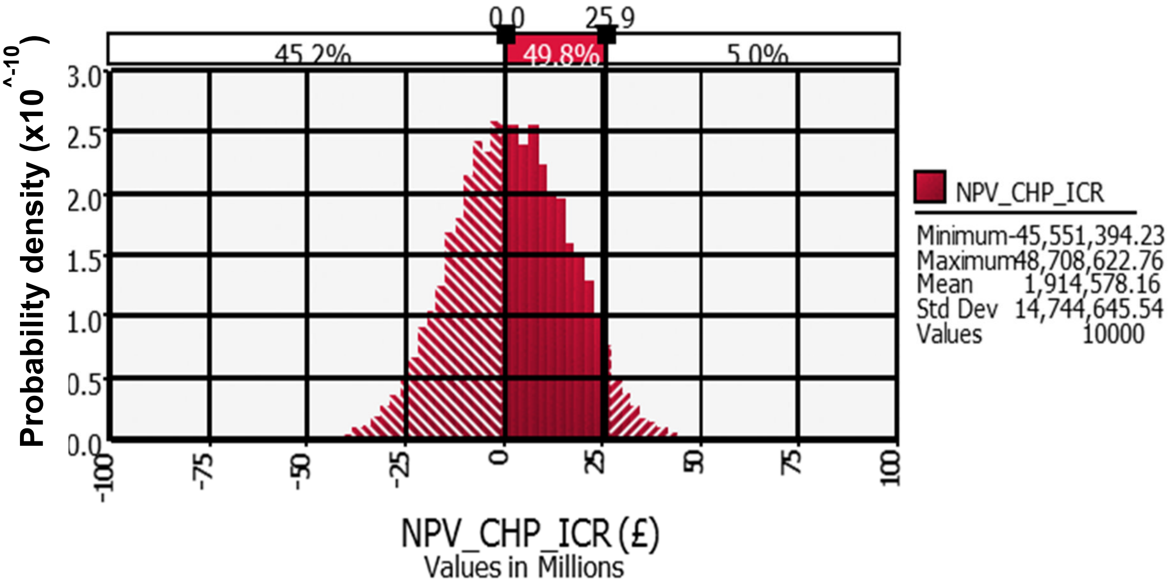


Figure 7-47 Triangular probability distribution of NPV for ICR, SS-ADIGT-CHP of SSRP

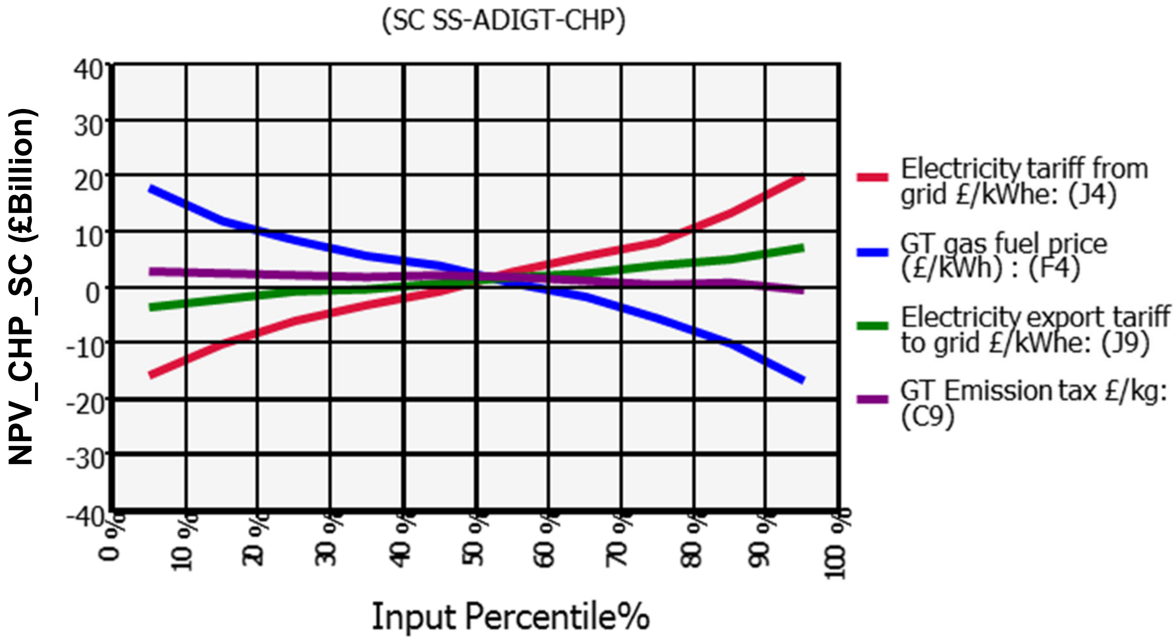


Figure 7-48 Sensitivity of NPV to changes in inputs values for SC SS-ADIGT-CHP of SSRP (Triangular distribution)

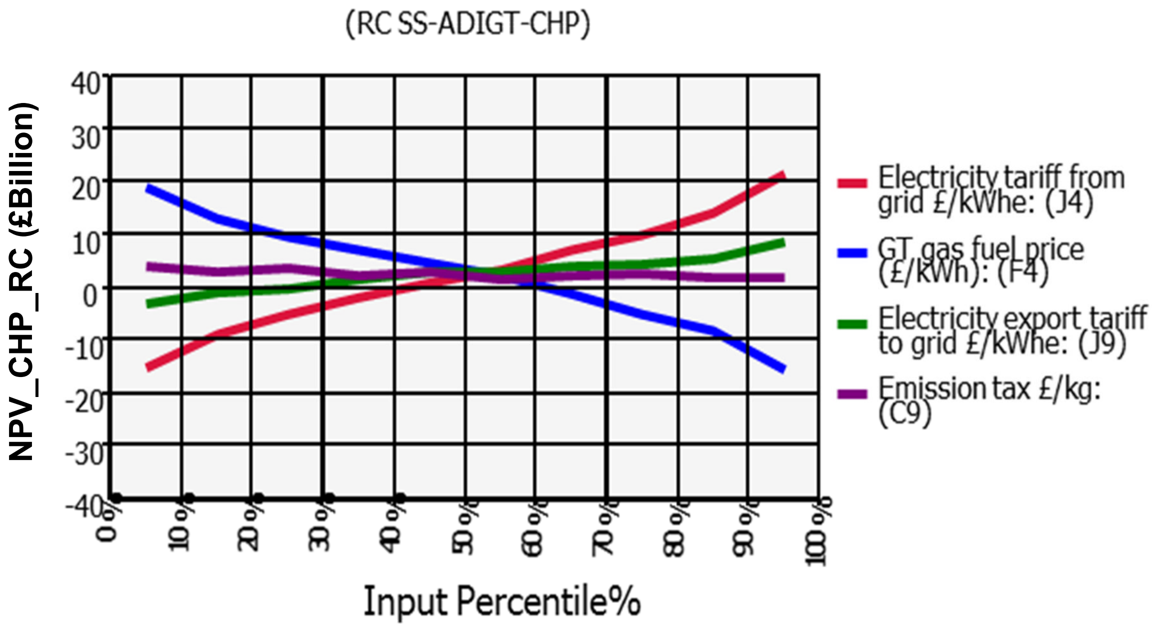


Figure 7-49 Sensitivity of NPV to changes in inputs values for RC SS-ADIGT-CHP of SSRP (Triangular distribution)

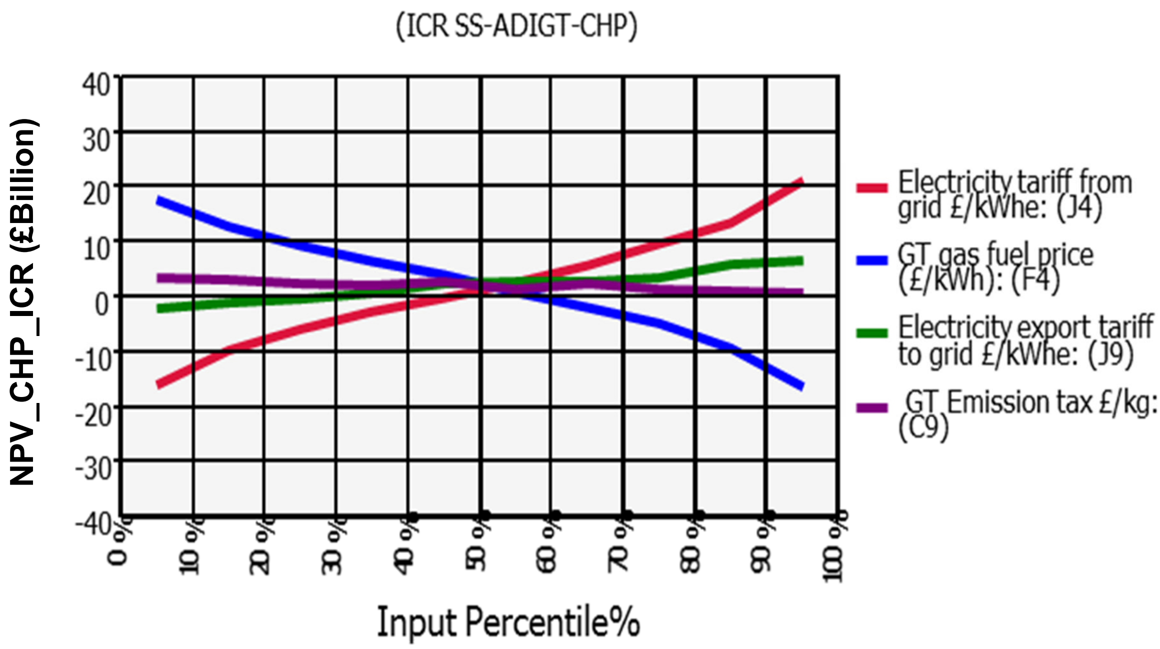


Figure 7-50 Sensitivity of NPV to changes in inputs values for ICR SS-ADIGT-CHP of SSRP (Triangular distribution)

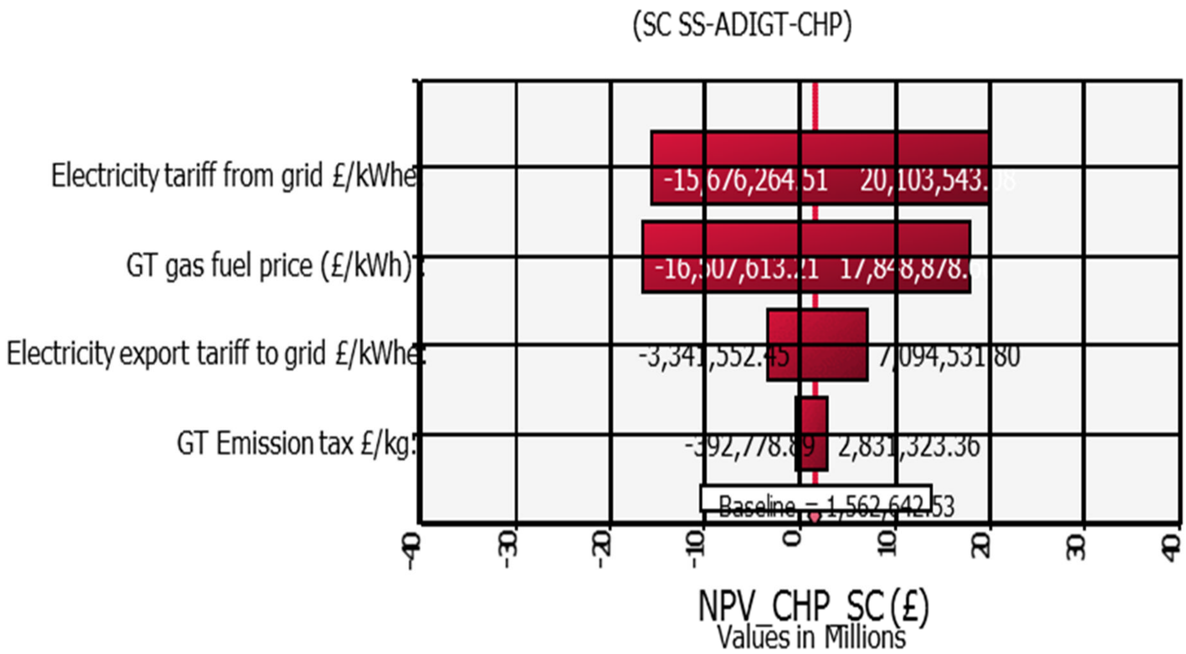


Figure 7-51 Inputs ranked by effects on NPV for SC SS-ADIGT-CHP of SSRP (Triangular distribution)

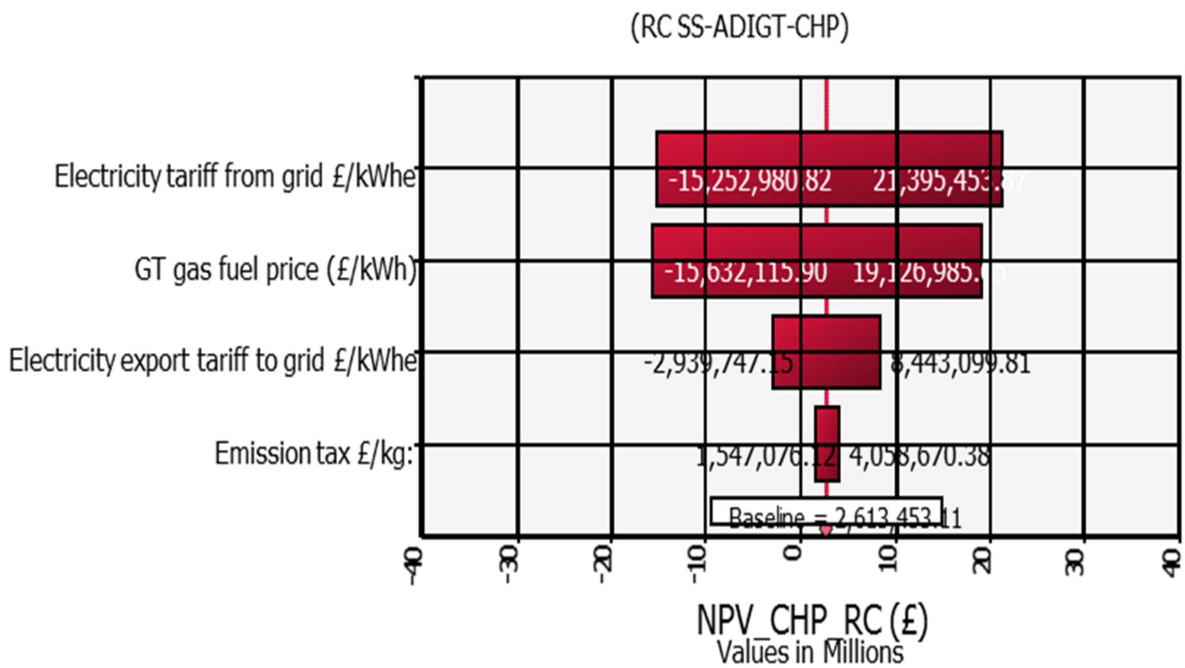


Figure 7-52 Inputs ranked by effects on NPV for RC SS-ADIGT-CHP of SSRP (Triangular distribution)

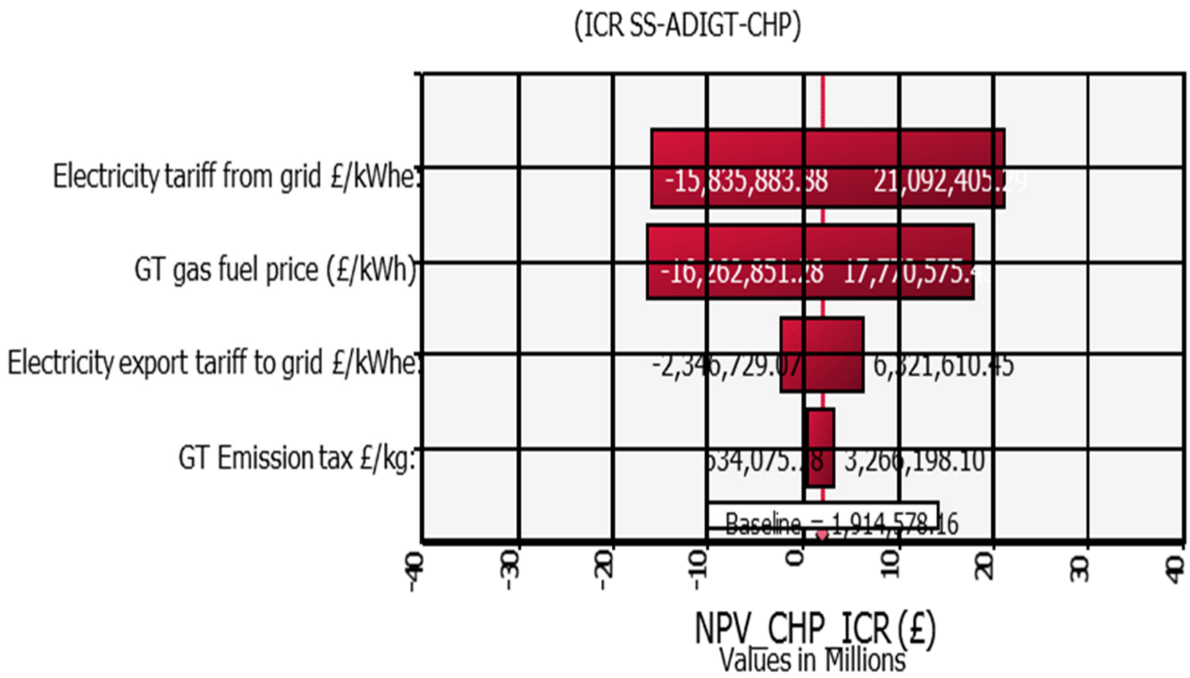
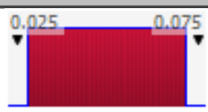
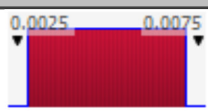


Figure 7-53 Inputs ranked by effects on NPV for ICR SS-ADIGT-CHP of SSRP (Triangular distribution)

7.3.4.1.5 Uniform distribution of inputs for SSRP CHP

Uniform frequency distributions are defined for the inputs as presented in Table 7-22

Table 7-22 Uniform distribution of inputs defined for SSRP CHP.

Inputs	Uniform graph	Minimum	Mean	Maximum	5th percentile	95th percentile
Electricity tariff from grid £/kWhe:		0.06	0.1	0.15	0.064	0.145
Electricity export tariff to grid £/kWhe :		0.03	0.05	0.07	0.032	0.068
GT gas fuel price (£/kWh):		0.03	0.05	0.08	0.032	0.077
Emission tax £/kg :		0.003	0.005	0.007	0.0032	0.0068

7.3.4.1.6 Results of uniform distribution risk analysis for SSRP CHP

Following the same procedure of section 7.3.4.1.1, the results of probability distributions of NPV for the three cycles are as presented in Figure 7-54 to Figure 7-56. Besides, the results of sensitivity of NPV to variations in values of inputs are shown in Figure 7-57 to Figure 7-59, whereas the rankings of inputs by their effects on NPV are shown in Figure 7-60 to Figure 7-62.

From the uniform distribution results the probability of having less than zero or zero NPV which is the range for making loss in investment is obtained as 48.3% for SC, 46.4% for RC, and 47.5% for ICR as presented in Figure 7-54 to Figure 7-56.

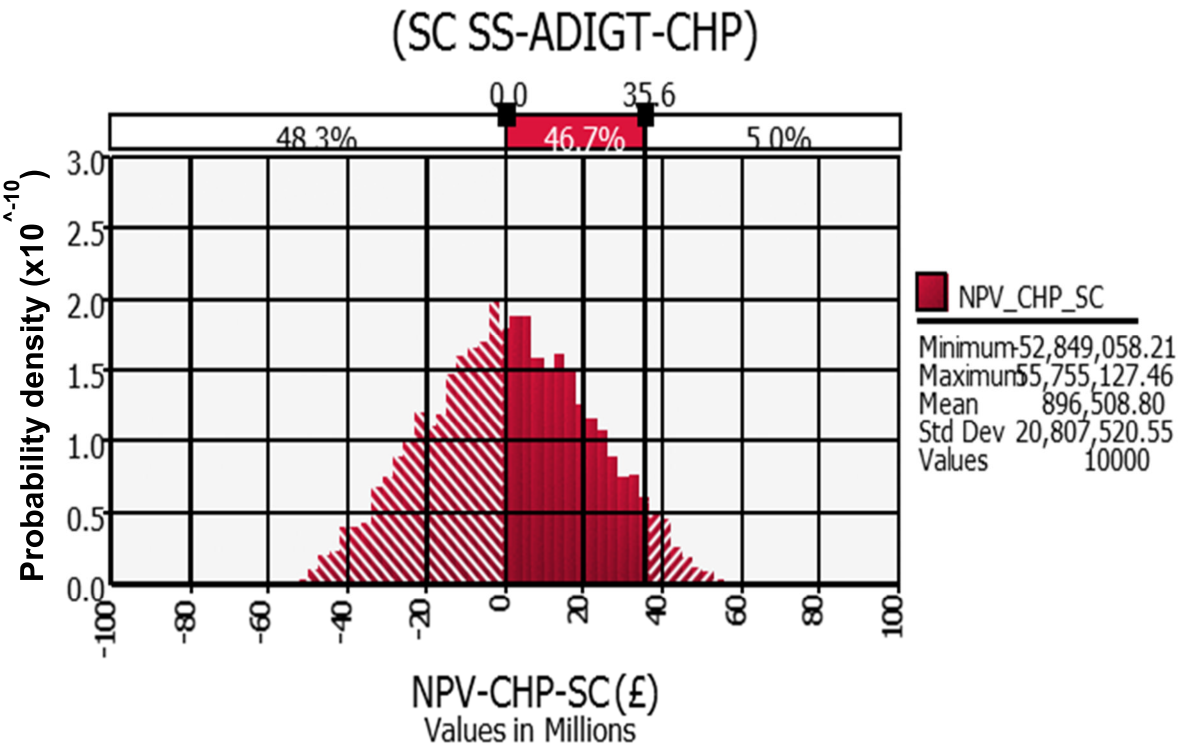


Figure 7-54 Uniform probability distribution of NPV for SC SS-ADIGT-CHP of SSRP

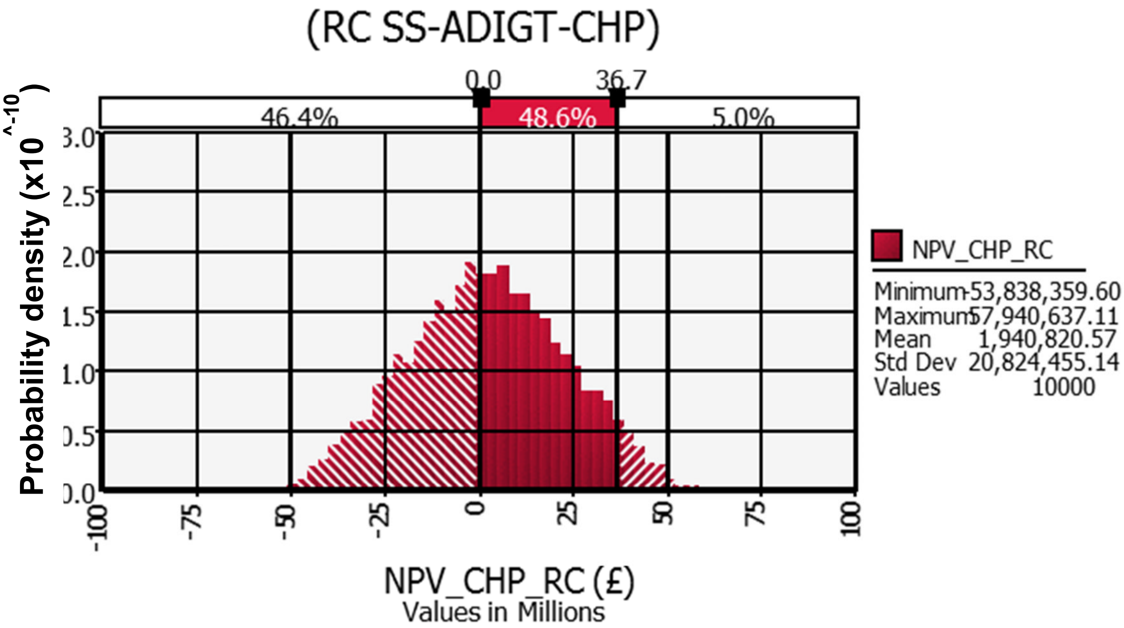


Figure 7-55 Uniform probability distribution of NPV for RC SS-ADIGT-CHP of SSRP

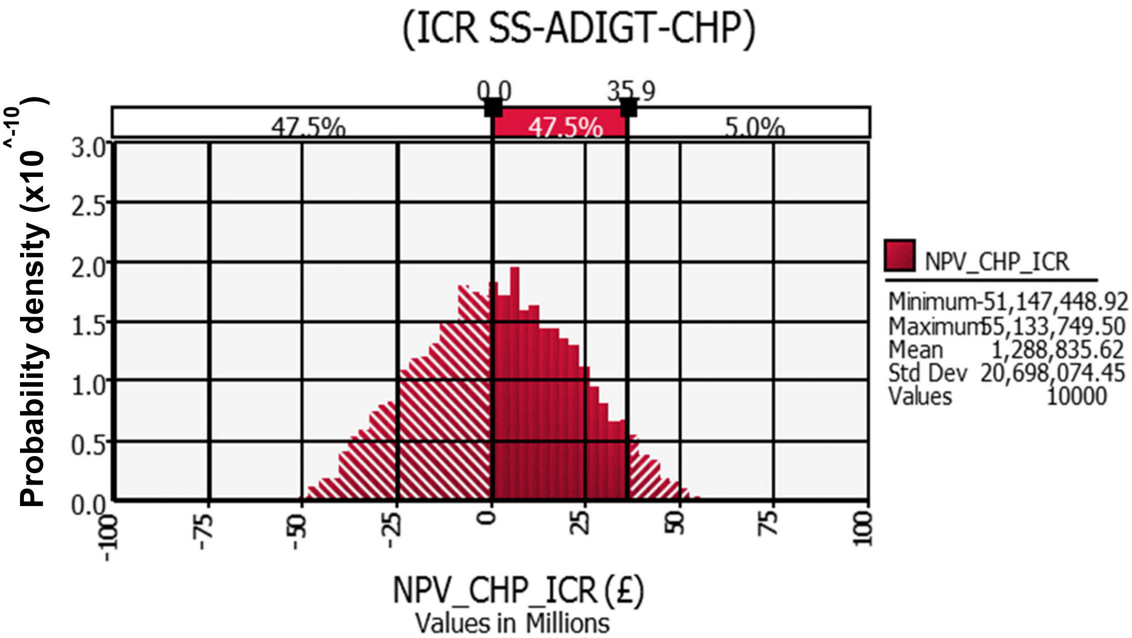


Figure 7-56 Uniform probability distribution of NPV for ICR SS-ADIGT-CHP of SSRP

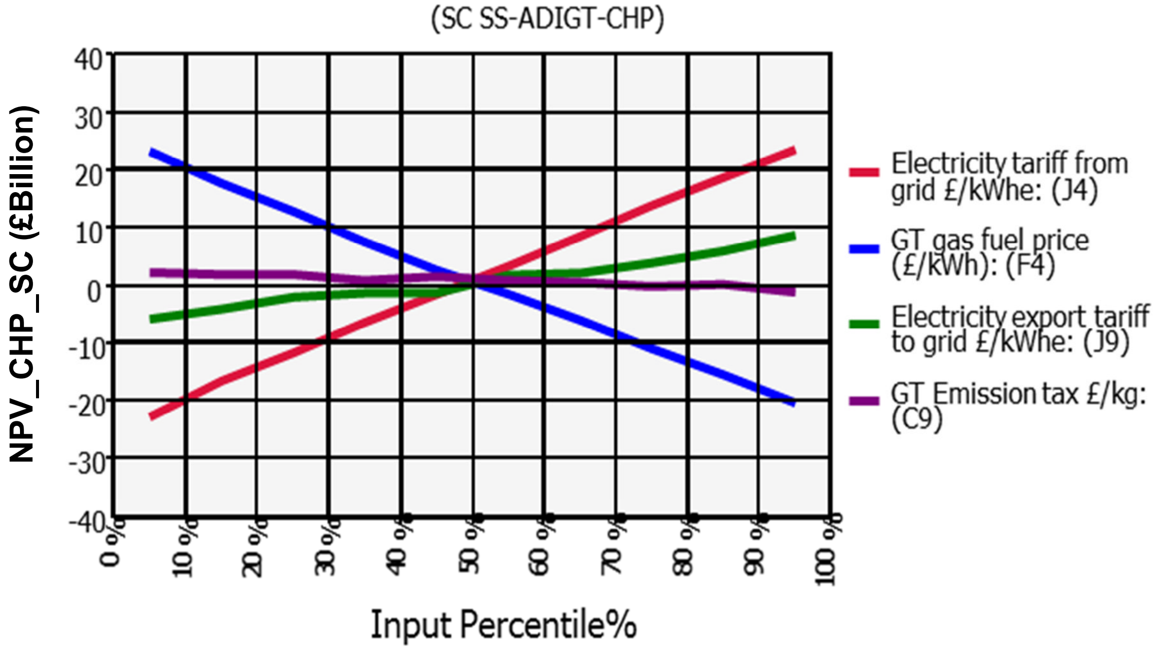


Figure 7-57 Sensitivity of NPV to changes in inputs values for SC SS-ADIGT-CHP of SSRP (Uniform distribution)

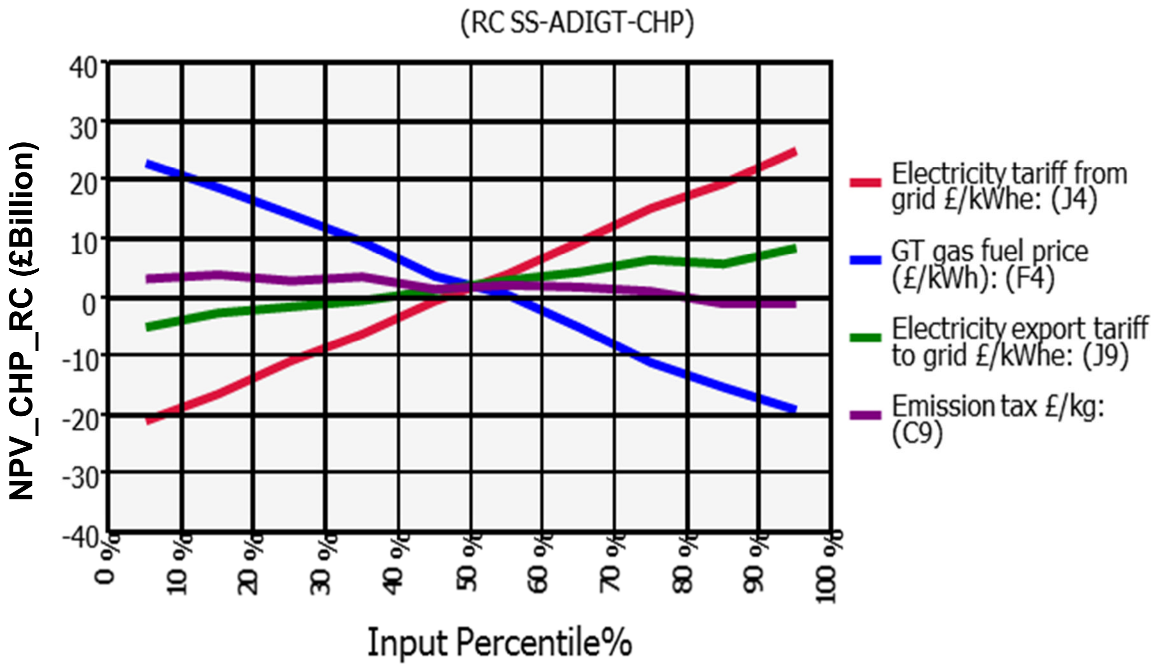


Figure 7-58 Sensitivity of NPV to changes in inputs values for RC SS-ADIGT-CHP of SSRP (Uniform distribution)

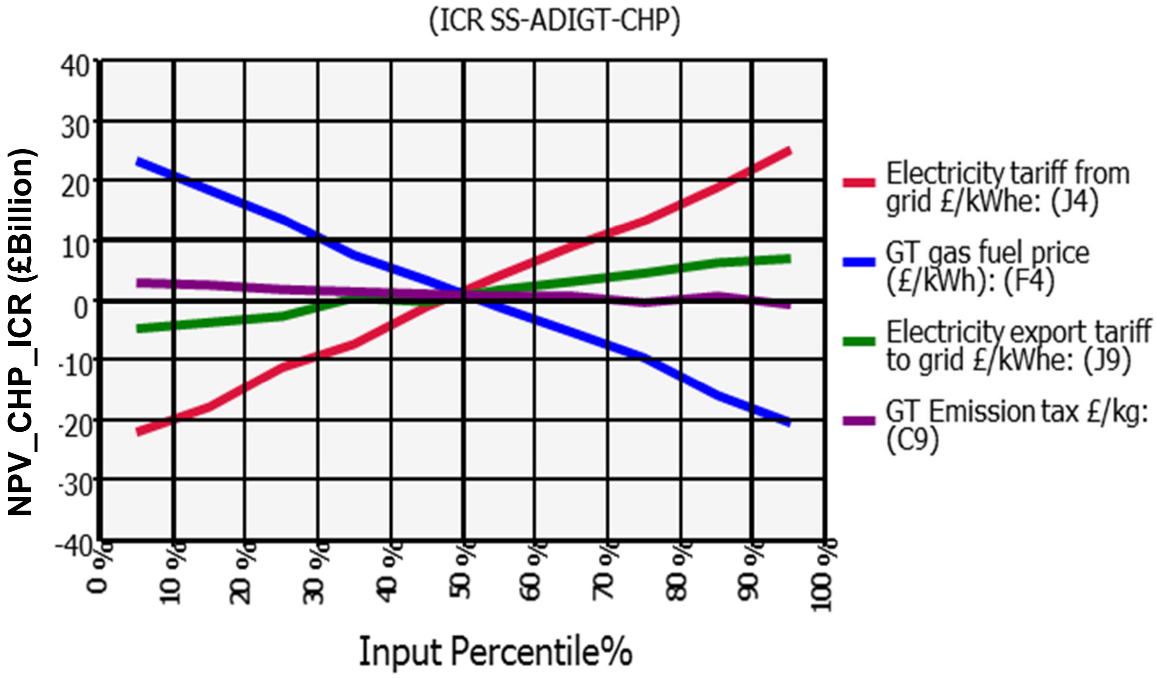


Figure 7-59 Sensitivity of NPV to changes in inputs values for ICR SS-ADIGT-CHP of SSRP (Uniform distribution)

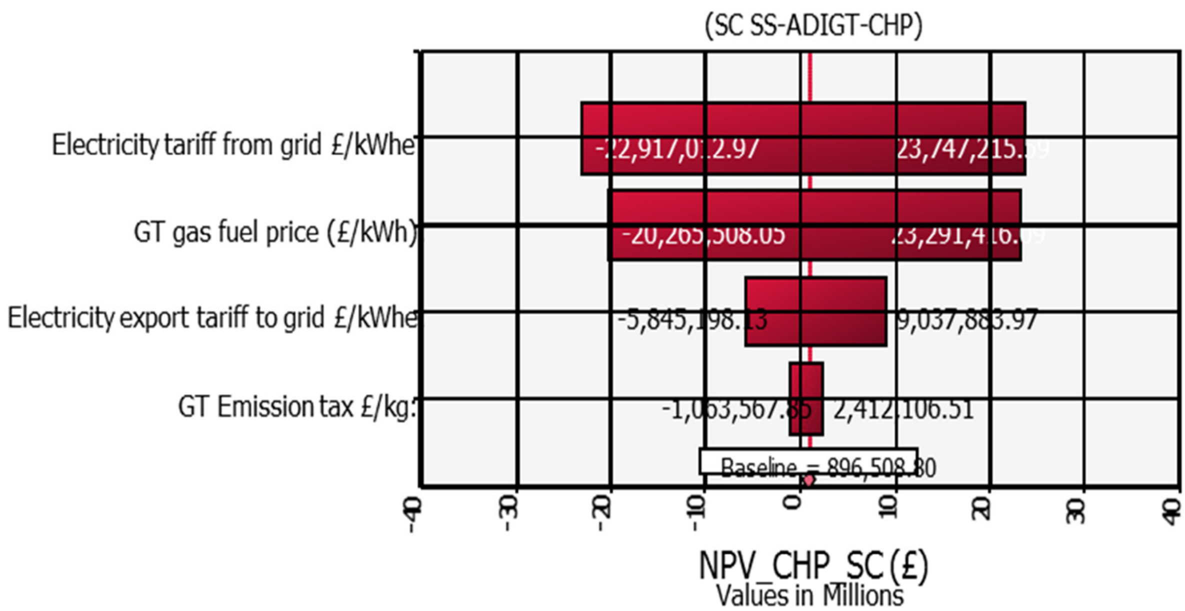


Figure 7-60 Inputs ranked by effects on NPV for SC SS-ADIGT-CHP of SSRP (Uniform distribution)

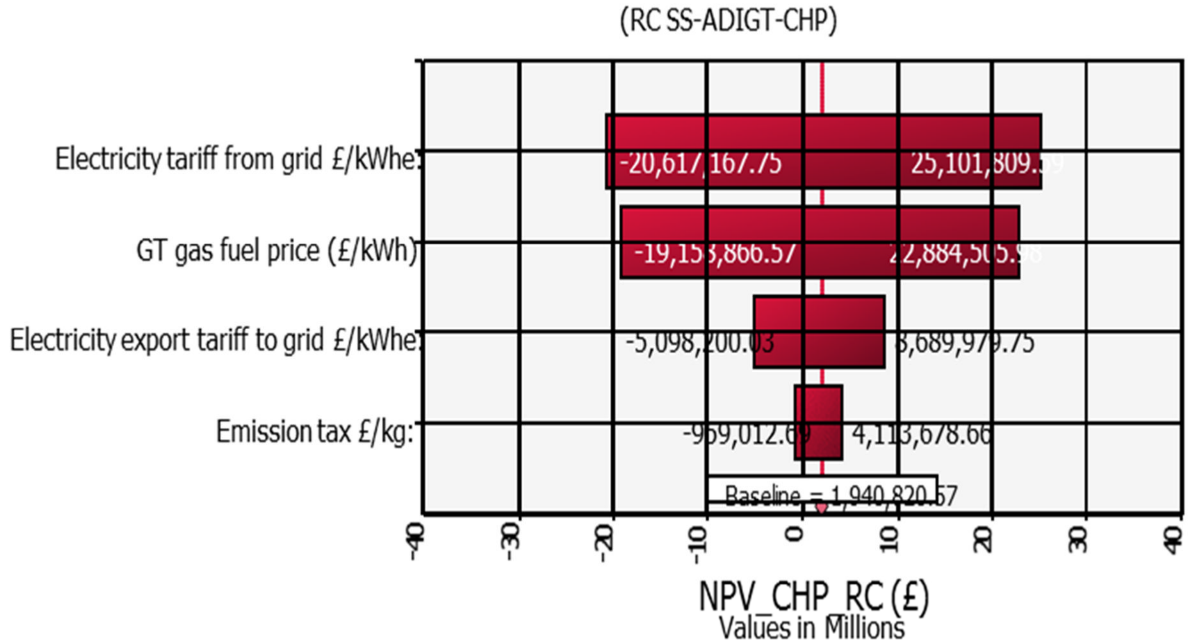


Figure 7-61 Inputs ranked by effects on NPV for RC SS-ADIGT-CHP of SSRP (Uniform distribution)

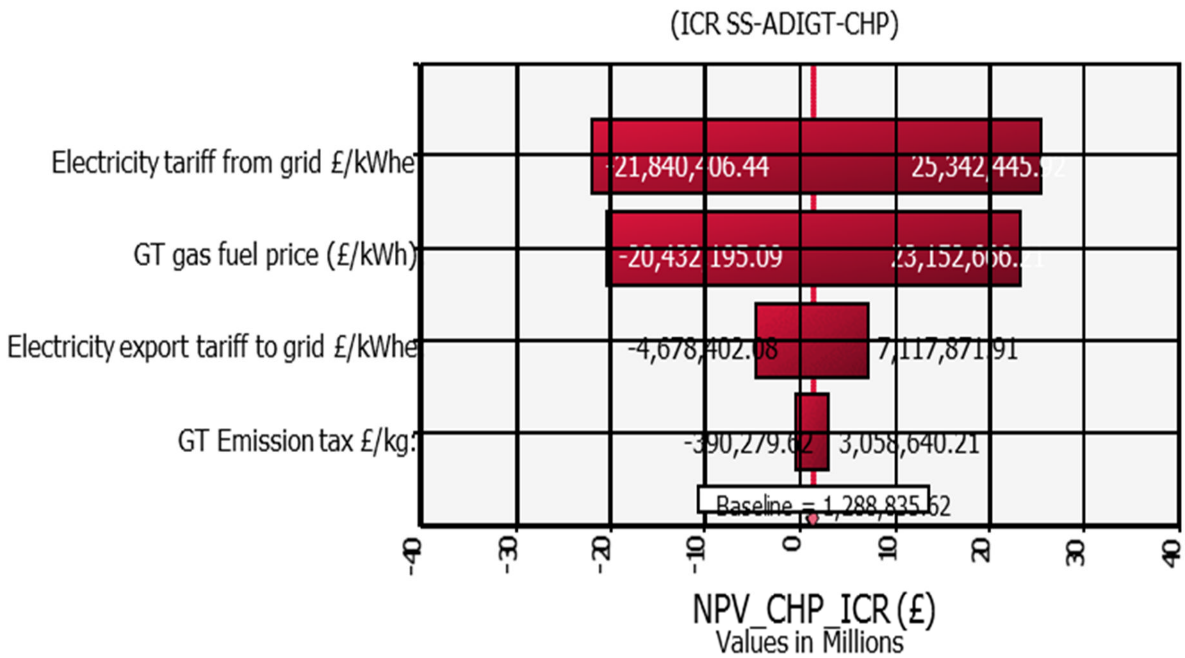


Figure 7-62 Inputs ranked by effects on NPV for ICR SS-ADIGT-CHP of SSRP (Uniform distribution)

7.3.4.1.7 NPV sensitivity analysis results of SSRP ADIGT-CHP

The outcome of sensitivity analysis of NPV of SSRP ADIGT-CHP shows that change in grid electricity price has the greatest effect on mean NPV followed by that of gas turbine fuel price, whereas variation in electricity export price has the least effect for all three engine cycles. This is presented in Figure 7-42 to Figure 7-44, Figure 7-51 to Figure 7-53, and Figure 7-60 to Figure 7-62. This trend is replicated for normal, triangular, and uniform distribution of inputs.

Similarly, for all three types of distributions, it is also observed as shown in Figure 7-39 to Figure 7-41, Figure 7-48 to Figure 7-50, and Figure 7-57 to Figure 7-59, that as price of grid electricity increases, mean NPV increases, for all three engine cycles. This is because the main benefit of the CHP plant is to save cost of purchasing power from the grid. Of course this trend is expected because the higher the grid electricity price, the higher the saved cost of grid electricity which adds to annual net savings. Also from the annual power generation/consumption of the plant, power purchased from the grid is far lower than power generated on site annually, hence the huge amount in saved grid electricity cost. More so, mean NPV increases very slightly with increase in electricity export price because very minute quantity of electricity is exported. On the other hand, as gas turbine fuel price and emission tax increase, mean NPV decreases. This is true as gas turbine fuel price is huge expense (cash outflow). Change in emission tax has very little or insignificant effect on mean NPV perhaps due to the minute amount of the unit price paid as emission penalty.

Still explaining the sensitivity curves of Figure 7-39 to Figure 7-41, Figure 7-48 to Figure 7-50, and Figure 7-57 to Figure 7-59, it could be observed that mean NPV rightly occurs in the scenario of input values that fall in the 50th percentile of input distributions. For scenario of input values above the 50th percentile (51% - 95%) of input distributions, and for same reasons as stated in the above paragraph, it is found that: NPV increases above the mean value with grid power tariff; decreases below mean value with GT fuel price; increases very slightly with electricity export price; and decreases very slightly with GT emission tax. On the other hand, for scenario of input values below the 50th percentile (5% - 49%) of input distributions: NPV becomes lower than the mean value with grid power tariff; increases above the mean value with GT fuel price; decreases very slightly with electricity export price; and increases very slightly with GT emission tax. The import of these results is that GT fuel price and grid power tariff are very significant input quantities in the life-cycle cost of the CHP project, and therefore require further priority attention and investigation.

Sensitivity analysis results of the triangular and uniform distribution simulation are similar to those of normal distribution, except that the range of values of mean NPV is narrower in the case of uniform distribution, and narrowest in the case of triangular distribution. Nevertheless, probability density of mean NPV is higher in the case of uniform distribution than normal distribution, and highest in the case of triangular distribution. This explains why the sensitivity curves are less steep in the case of triangular distribution.

7.3.5 Overall results for SSRP ADIGT-CHP economic analysis

The outcome of the techno-economic assessment of the SSRP ADIGT-CHP indicates that all three cycle configurations, SC, RC, and ICR SS-ADIGT-CHP register positive NPV and are profitable than the conventional case. However, the scenario of RC SS-ADIGT-CHP recorded the highest profit in NPV, the shortest payback period, and the highest IRR, followed by the ICR SS-ADIGT-CHP. This economic performance is shown in Figure 7-32 to Figure 7-34. It was found that the percentage savings in operational cost of SC, RC, and ICR cycle SS-ADIGT–CHP over the conventional case (grid power plus on-site boiler) are 29.1%, 30.2%, and 30.0% respectively as presented in Figure 7-35. The bulk of annual net savings of the RC SS-ADIGT-CHP comes from sale of excess steam. This sale is observed to be huge in the case of RC SS-ADIGT-CHP than in SC and ICR SS-ADIGT-CHP. The much excess steam is as a result of high temperature - high heat content of the exhaust gas of the RC SS-ADIGT compared to those of the SC and ICR cycles.

The avoided or saved electricity and steam cost, grid electricity, and boiler heat cost, are the same in all three scenarios due to the constant (routine) consumption rate of the process plant. Nevertheless, capital/installation cost was highest in the case of ICR SS-ADIGT-CHP, followed by IC SS-ADIGT-CHP, of course due to additional components and complexity (from intercooler, and recuperator). Furthermore, highest emission cost was incurred in the scenario of SC SS-ADIGT-CHP than the advanced cycles, due to least GT thermal efficiency and highest emission index of the former.

More so, ICR SS-ADIGT-CHP incurred the least GT fuel and emission costs due to its highest GT thermal efficiency and least emission index. Besides, it is noteworthy that of all the annual cost elements, GT fuel cost contributes the largest percentage in all three scenarios. More so, from the risk assessment, the probability of incurring loss in investment as defined by tendency of having negative mean NPV is lowest in the RC SS-ADIGT-CHP and highest in SC SS-ADIGT-CHP. This trend is the same in all three types of distributions studied. Besides, it is observed that IRR of the SS-ADIGT-CHP cycle options increases as NPV increases, whereas SPBP decreases with increasing NPV, as shown in the combination of Figure 7-32, Figure 7-33, and Figure 7-34.

As referenced in section 7.2.5, the results of SS-ADIGT-CHP economic analysis compare favourably with trends available in the literature. For instance, A 6.5MWe gas turbine unit was identified to be the largest energy saving measure for a small refinery (Paramount Petroleum Corp's asphalt refinery in Paramount (CA) in the United State. It was predicted that this CHP would result in annual energy saving worth of $3.8 million and has a payback period of 2.5 years (U.S DOE-OIT, 2003). Besides, it was found that the CHP would reduce the risk of power outages for the refinery, and would also reduce emission (Worrell and Galitsky, 2005). Besides, an instance has been reported of a 1MW CHP plant in the UK predicted to have an IRR of 13.4% and SPBP of 3.5 years with 20 years life-cycle analysis. Same report mentioned another 20 years life-cycle analysis of a 12 MW CHP in the UK that was predicted to have an IRR of 12.4% and SPBP of 5.7 years (Merše et al, 2011).

7.4 Chapter summary

In this chapter the following are described

- TERA framework is adapted to ADIGT-CHP in the petrochemical industry by way of conducting two case studies: Large-scale refinery and chemical plant CHP(LSRCP-CHP), and small-scale refinery plant CHP (SSRP-CHP).
- An economic evaluation model is developed and deployed in the two case studies.
- Assessment, prediction, and comparison are done of the techno-economic viability of SC, IC, and ICR large-scale ADIGT-CHP, and SC, RC, and ICR small-scale ADIGT-CHP, over the conventional case of grid power plus on-site boiler in the petrochemical industry in their respective case studies.
- The model implements the assessment by estimating NPV, IRR, and SPBP for all the ADIGT-CHP cycle options in their various categories given inputs from technical performance parameters such as GT fuel flow, power output, exhaust heat recovery, steam flow, emission index, of the engines with various respective costs.
- In addition, the model utilises as inputs the capital/installation costs of GT-CHP and boilers, boiler fuel and emission costs, investment Loan, interest on loan, O & M cost, and market discount rate.
- It is found that the percentage savings in operational costs of SC, IC, and ICR cycle large-scale ADIGT–CHP over the conventional case are 20.7%, 21.6%, and 21.4% respectively.
- IC exhibits better NPV, SPBP, and IRR than SC and ICR cycles over the conventional case in the large-scale ADIGT-CHP category.

Nevertheless, all three cycle options are profitable than the conventional case.

- Steam flow is found to be more in SC than in IC and ICR in the large-scale ADIGT-CHP cycles.
- SC exhibits better CHP efficiency than IC and ICR in the large-scale ADIGT-CHP category.
- Risk assessment of large-scale ADIGT-CHP shows that the probability of incurring loss in investment as defined by tendency of having negative mean NPV is lowest in the IC LS-ADIGT-CHP and highest in SC LS-ADIGT-CHP. This trend is the same in all three types of distributions studied: normal, triangular, and uniform distributions.
- It is observed that the percentage savings in the operational cost of SC, RC, and ICR small-scale ADIGT-CHP over the conventional case are 29.1%, 30.9%, and 30.0% respectively.
- RC exhibits better NPV, SPBP, and IRR than SC and ICR cycles over the conventional case in the small-scale ADIGT-CHP category. Nevertheless, all three cycle options are profitable than the conventional case.
- Steam flow is found to be more in RC than in SC and ICR in the small-scale ADIGT-CHP cycles.
- RC exhibits better CHP efficiency than SC and ICR in the small-scale ADIGT-CHP category.
- Risk assessment of small-scale ADIGT-CHP shows that the probability of incurring loss in investment as defined by tendency of having negative mean NPV is lowest in the RC SS-ADIGT-CHP and highest in SC SS-ADIGT-CHP. This trend is the same in all three types of distributions studied: normal, triangular, and uniform distributions.
- GT fuel price and grid power tariff are very significant input quantities in the life-cycle cost of CHP project, and impact more on NPV and by extension on IRR, and payback period.

8 CONCLUSIONS AND FURTHER RESEARCH

8.1 Conclusions

8.1.1 Aim of research achieved

In the introduction of this research the aim was clearly stated as:

- **To adapt techno-economic and environmental risk analysis (TERA) framework for aero-derivative industrial gas turbines combined-heat-and-power (ADIGT-CHP) in the petrochemical industry**.

This aim can be said to have been achieved judging by rigorous implementation of the set objectives as explained in section 8.1.2 below.

8.1.2 Objectives implemented and conclusions

A number of objectives were targeted in order to achieve the aim recalled in the preceding section.

The first objective formed part A of this research, which is analysis of technical performances of simple and advanced cycle helicopter engines. This objective is meant to establish the characteristics and performances of helicopter engines that were subsequently converted to SS-ADIGT for CHP application in the petrochemical industry. From the work done in this part of the research, it could be concluded that:

- All three advanced cycle helicopter engines (RC, ICR, and LPC zero-staged) configurations have lower s.f.c. and higher thermal efficiencies than the simple base engine cycle at both DP and OD.
- The percentage increases in thermal efficiencies of engine cycle with LPC zero-staged, RC engine, and ICR engine cycles, over simple cycle at DP were found to be 2.1%, 20.6%, and 24.2% respectively, whereas percentage reduction in specific fuel consumption in these cycles over simple cycle at DP are 2.6%, 17.3%, and 21.1% respectively.
- At DP, the ICR cycle helicopter engine exhibits the lowest s.f.c. of 0.0664kg/MWs and highest thermal efficiency of 34.9% followed by the RC, and then the LPC zero-staged, whereas the SC exhibits the highest s.f.c of 0.0827kg/MWs and lowest thermal efficiency of 28.1%. However, it was noted that the addition of intercooler, recuperators, and extra stage of compression, would actually increase the capital/installation cost of the advanced cycles than that of the simple cycle.

Pursuing the remaining number of objectives formed part B of the research, which pertains to techno-economic and environmental risk assessment of ADIGT-CHP application in the petrochemical industry. In this regard, the first objective targeted is that of converting helicopter engines analysed in part A to SS-ADIGT. This objective is accomplished, having the performances of the SS-ADIGT cycles analysed too. Also, the objective of analysing technical performances and estimating engine emissions of ADIGT engines is achieved. From the work carried out it could be concluded that:

- RC and ICR SS-ADIGT cycles have increased thermal efficiencies and lower combustor heat rates than the simple cycle.
- The percentage increases in thermal efficiencies of RC and ICR SS-ADIGT cycles over simple cycle at DP were found to be 13.5%, and 14.5% respectively, whereas percentage reduction in heat rates in these cycles over simple cycle at DP are 12.3% and 12.9% respectively.
- At DP, the ICR SS-ADIGT cycle is found to exhibit the lowest heat rate of 3.229MJ/MWs and highest thermal efficiency of 33.9% followed by the RC which shows 3.251MJ/MWs and 33.6% respectively, whereas the SC exhibits the highest heat rate of 3.708MJ/MWs and lowest thermal efficiency of 29.6%.
- Similarly, for both LS1-ADIGT and LS2-ADIGT, the IC and ICR cycles possess increased thermal efficiencies and reduced combustor heat rates than the simple engine.
- The percentage increases in thermal efficiencies of IC and ICR LS1-ADIGT cycles over simple cycle at DP were found to be 3.2%, and 3.4% respectively, whereas percentage reduction in heat rates in these cycles over simple cycle at DP are 2.7% and 2.8% respectively.
- At DP, the ICR LS1-ADIGT cycle is found to exhibit the lowest heat rate of 2.602MJ/MWs and highest thermal efficiency of 42% followed by the IC which shows 2.605MJ/MWs and 41.9% respectively, whereas the SC exhibits the highest heat rate of 2.676MJ/MWs and lowest thermal efficiency of 41%
- The percentage increases in thermal efficiencies of IC and ICR LS2-ADIGT cycles over simple cycle at DP were found to be 2.42%, and 0.94% respectively, whereas percentage reduction in heat rates in these cycles over simple cycle at DP are 2.37% and 0.93% respectively.
- At DP, the IC LS2-ADIGT cycle is found to exhibit the lowest heat rate of 2.343MJ/MWs and highest thermal efficiency of 46.7% followed by the ICR which shows 2.377MJ/MWs and 46% respectively, whereas the SC exhibits the highest heat rate of 2.399MJ/MWs and lowest thermal efficiency of 45.7%.
- The advanced cycle ADIGT engines, possessing increased thermal efficiencies, show lower total emissions than simple cycle.

More so, the objective of identification of environmentally friendly Brayton cycles in the petrochemical industry is accomplished after going through the literatures. From this task it could be concluded that:

- ADIGT-CHP cycles would be environmentally friendly Brayton cycles of good repute that would be a measure for large heat energy savings and reduction of global warming in the petrochemical industry.

Following is the objective of modelling and analysing technical performance of ADIGT-CHP cycles which is achieved. The analysis led to the conclusions that:

- For SS-ADIGT-CHP, better CHP efficiency is exhibited by RC and ICR cycles than SC engine. The CHP efficiencies of RC, ICR, and SC SS-ADIGT-CHP cycles were found to be 92%, 82%, and 75% respectively.
- For the SS-ADIGT-CHP, RC engine produces the highest HRSG duty. The HRSG duties were found to be 3171.3kW for RC, 2621.6kW for ICR, and 3063.1kW for SC.
- For both LS1-ADIGT-CHP and LS2-ADIGT-CHP, the SC exhibits the highest CHP efficiency and HRSG duty than IC and ICR engine cycles.
- For the LS1-ADIGT-CHP, the CHP efficiencies of SC, IC, and ICR cycles were found to be 75%, 64%, and 66% respectively, whereas the HRSG duties are respectively 45632.1kW, 31199.7kW, and 32553.8kW.
- For the LS2-ADIGT-CHP, the CHP efficiencies of SC, IC, and ICR cycles were found to be 78%, 68%, and 69% respectively, whereas the HRSG duties are respectively 90236.3kW, 63624.5kW, and 67349.8kW.

Furthermore, the remaining three objectives targeted in part B were accomplished in same sets of tasks carried out. These include the objectives of: (a) techno-economic and risk analysis of simple and advanced cycle ADIGT-CHP in the petrochemical industry, (b) development of a techno-economic model to assess the viability of various ADIGT-CHP cycles in the petrochemical industry, and (c) providing a multi-disciplinary framework for comparing investments in ADIGT plant equipment for application in CHP in the petrochemical industry. From the tasks implemented in these regards, the following conclusions could be made:

- A techno-economic model has been developed that can evaluate the criteria of assessing economic viability of ADIGT-CHP cycle options for generating steam and power simultaneously in the petrochemical industry over the conventional case of grid power plus on-site boiler. These criteria are SPBP, NPV, and IRR, given inputs such as GT fuel flow, power output, exhaust heat recovery, steam flow, total emission, of the engines with various respective costs, in addition to capital/installation costs of GT-CHP and boilers, boiler fuel and emission costs, investment loan, interest on loan, O & M fixed and variable costs, and market discount rate.

- Savings exist in operational costs of ADIGT-CHP over and above the conventional case. Hence, for both SS-ADIGT-CHP, and LS-ADIGT-CHP cases, all ADIGT-CHP applications are profitable than the conventional case. The percentage savings in operational costs of SC, RC, and ICR SS-ADIGT-CHP over and above the conventional case were found to be 29.1%, 30.9% and 30% respectively. The percentage savings in operational costs of SC, IC, and ICR LS-ADIGT-CHP over and above the conventional case were found to be 20.7%, 21.6% and 21.4% respectively.
- For LS-ADIGT-CHP, the probability of incurring loss in investment as defined by tendency of having negative mean NPV is lowest in the IC ADIGT-CHP and highest in SC ADIGT-CHP. This trend is the same in all three types of distributions studied: normal, triangular, and uniform distributions. This is because IC exhibits better NPV, SPBP, and IRR than SC and ICR cycles over and above the conventional case in this ADIGT-CHP category. For instance, the payback period for SC, IC, and ICR LS-ADIGT-CHP cycles were estimated to be 4.8, 4.6, and 4.7 years respectively, whereas the IRR were respectively found to be 18.3%, 19%, and 18.7% at same market discount rate of 10%.
- For small-scale ADIGT-CHP, the probability of incurring loss in investment as defined by tendency of having negative mean NPV is lowest in the RC ADIGT-CHP and highest in SC ADIGT-CHP. This trend is the same in all three types of distributions studied: normal, triangular, and uniform distributions. This is because RC exhibits better NPV, SPBP, and IRR than SC and ICR cycles over and above the conventional case in the SS-ADIGT-CHP category. For instance, the payback period for SC, RC, and ICR SS-ADIGT-CHP cycles were estimated to be 6.5, 6.1, and 6.3 years respectively, whereas the IRR were respectively found to be 12.9%, 13.9%, and 13.1% at same market discount rate of 10%.
- GT fuel price and grid power tariff are very significant input quantities in the life-cycle cost of CHP project, and impact more on NPV and by extension on IRR, and payback period
- The general performances and economic viabilities of the ADIGT-CHP cycles would greatly depend on the climatic conditions of the region/area of operation.
- A multi-disciplinary framework for comparing investments in ADIGT plant equipment for application in CHP in the petrochemical industry has been provided which comprise of engine performance, emissions, economic, and risk, modules.

- This multi-disciplinary framework is a preliminary design tool that would actually aid assets managers or product development engineers to make good choice of ADIGT-CHP cycle options in the petrochemical industry. Hence, **the research question** (which is how one would make the choice of aero-derivative industrial gas turbines CHP cycle option in the petrochemical industry that would produce good return on investment, considering economic benefits) could be said to has been answered.
- Therefore **the aim of this research**, which is to adapt techno-economic and environmental risk analysis (TERA) framework for aero-derivative industrial gas turbines combined-heat-and-power (ADIGT-CHP) in the petrochemical industry, could be said to has been achieved.

This research has made two **contributions to knowledge,** namely:

- Development of a model for assessing, predicting, and comparing the techno-economic viability of simple and advanced cycle ADIGT-CHP application in the petrochemical industry over the conventional case of grid power and on-site boiler in terms of NPV, SPBP, and IRR.
- Derivation of simple and advanced cycles small-scale ADIGT-CHP from helicopter gas turbine engines.

8.1.3 Gains of the techno-economic model

The ADIGT-CHP techno-economic model developed in this research exhibits the following capabilities which are lacking in other models that have been reviewed:

- It accounts for cost of total emissions to include NO_x, CO, CO_2, and H_2O_{vapour}. Previous models account for emission cost of only CO_2.
- It is able to compare viability of various ADIGT-CHP cycle options with one another as well as with conventional case of grid power plus on-site boiler to determine cost savings of using CHP. Previous models only estimate savings of one GT-CHP cycle with respect to conventional case.
- It considers NPV risk analysis using Latin Hypercube sampling technique which gives a better spread of sampled inputs across the percentiles of a frequency distribution than Monte Carlo sampling method that clusters samples of inputs during iterations.

8.2 Research limitations

- Economic and environmental risk assessment of the helicopter engine cycles analysed in part A of this research was not considered due to time and its complexity.

- The techno-economic model developed in this research does not account for depreciation and creep life of the CHP plant.

8.3 Further research

The analysis conducted in part A of this research which stemmed from the objective of analysing the technical performances of simple and advanced cycle helicopter gas turbines is limited. This is because economic and environmental risk assessment of the helicopter engine cycles was not considered due to time and its complexity. This limitation needs to be addressed as further research on:

- Techno-economic and environmental risk assessment of helicopter gas turbines on offshore mission to oil/gas rig, in which case the helicopter engines analysed in part A of this project could be assessed for their economic viability for offshore mission application conveying crew members to oil/gas platforms.

Besides, the techno-economic model developed in this research does not account for depreciation and creep life of the CHP plant as salvage value was assumed to be the cost of disposal of scrap plant. This limitation of the model needs to be addressed as further work on:

- Accounting for depreciation, creep life, and salvage value of ADIGT-CHP plants in the petrochemical industry.

More so, the much excess generated steam and power from the ADIGT-CHP that is exported could be harnessed or utilised for cooling purposes in both LSRCP and SSRP complexes, to further maximise CHP efficiencies. These needs could be handled as further work on:

- Tri-generation consideration for the large-scale ADIGT-CHP case study of LSRCP complex, and analysing for its techno-economic viability, and
- Tri-generation consideration for the small-scale ADIGT-CHP case study of SSRP complex, and assessing its techno-economic viability.

Finally, a thought about diversifying application of the small-scale ADIGT engines derived from helicopter engines could be made further research on:

- Techno-economic and environmental risk analysis of SS-ADIGT for rotating equipment drive in the petrochemical industry, whereby the small-scale ADIGT analysed in part B of this project could be assessed for their viability for application in industrial rotating equipment drive.

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APPENDICES

Appendix A Helicopter engines TURBOMATCH simulation files

A.1 Input and result files for SC helicopter engine performance simulation

```
TURBOMATCH SCHEME - Windows NT version (October 1999)
 LIMITS:100 Codewords, 800 Brick Data Items, 50 Station Vector
 15 BD Items printable by any call of:-
 OUTPUT, OUTPBD, OUTPSV, PLOTIT, PLOTBD or PLOTSV
  Input "Program" follows
 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
 !PERFORMANCE SIMULATION OF A TWO-SPOOL TURBOSHAFT!
 !HELICOPTER ENGINE WITH A FREE POWER TURBINE     !
 !INSPIRED BY TURBOMECCA MAKILA 2A ENGINE CORE    !
 !MODELLED BY BARINYIMA NKOI, MARCH 2012          !
 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
 OD SI KE CT FP
  -1
  -1
 INTAKE S1-2          D1-4           R100
 COMPRE S2-3           D5-10          R101   V5     V6
 ARITHY              D70-74
 COMPRE S3-4           D11,6,13-16      R104   V11
 PREMAS S4,5,13         D17-20
 ARITHY              D75-81
 BURNER S5-6           D21-23          R107
 MIXEES S6,13,7
 TURBIN S7-8           D24-31,115            V25
 DUCTER S8-9           D33-36          R108
 TURBIN S9-10          D37-45               V37    V38
 DUCTER S10-11          D46-49          R110
 NOZCON S11-12,1        D50            R111
 PERFOR S1,0,0          D37,52-54,111,100,107,0,0,0,0,0,0
 CODEND
!INTAKE
  1  0.0        !ALTITUDE:INLET
  2  0.0        !ISA DEVIATION
  3  0.0        !MACH NO
  4 -1.0        !PRESSURE RECOVERY
!COMPRE AXIAL
  5  0.85        !SURGE MARGIN
  6  -1.0        !ROTATIONAL SPEED
  7  2.5        !PRESSURE RATIO
  8  0.79        !COMPRE EFFICIENCY
  9  0.0        !ERROR SWITCH
 10  2.0        !COMPRE MAP
!COMPRE CENTRIFUGAL
 11  0.85        !SURGE MARGIN
 12  -1.0        !ROTATIONAL SPEED
 13  4.5        !PRESSURE RATIO
 14  0.79        !COMPRE EFFICIENCY
 15  1.0        !ERROR SWITCH
 16  4.0        !COMPRE MAP
!PREMAS
 17  0.913       !LAMBDA(W) {W5/W4}
 18  0.0        !DELTA(W)
 19  1.0        !LAMBDA(P)
```

```
 20  0.0        !DELTA(P)
!BURNER
 21  0.05       !PRESSURE LOSS
 22  0.99       !COMBUS EFFICIENCY
 23  -1.0       !FUEL FLOW CALCULATED
!COMPRE TURBINE
 24  0.0        !COMPRE TURBINE
 25  -1.0       !REL NON-D MASS FLOW
 26  -1.0       !REL NON-D SPEED
 27  0.88       !TURBINE EFFICIENCY
 28  -1.0       !REL ROT SPEED=COMPRE ROT SPEED
 29  2.0        !COMP NO
 30  1.0        !TURBINE MAP
 31  -1.0       !POWER LAW
 !AS IN 115     !COMWRK FOR COMP TURBINE
!DUCTER
 33  0.0        !DUCTER
 34  0.01       !PRESSURE LOSS
 35  0.0
 36  100000.0
!POWER TURBINE
 37  1567000.0  !POWER OUTPUT:POWER TURBINE(WATT)
 38  -1.0       !REL NON-D MASS FLOW
 39  -1.0       !REL NON-D SPEED
 40  0.89       !TURBINE EFFICIENCY
 41  1.0        !REL ROT SPEED
 42  0.0        !COMP NO
 43  5.0        !TURBINE MAP
 44  1000.0     !POWER LAW INDEX
 45  -1.0       !SET FOR POWER TURBINE
!DUCTER
 46  0.0        !DUCTER
 47  0.01       !PRESSURE LOSS
 48  0.0
 49  100000.0
!NOZCON
 50  -1.0       !SWITCH TO FIXED AREA
!PERFOR
 !AS IN 37      !POWER TURBINE:POWER OUTPUT
 52  1.0        !PROPELLER EFFICIENCY:PERFORMANCE
 53  0.0        !SCALING INDEX
 54  0.0        !SHAFT POWER
!ARITHY: COMPREAXIALPCN=COMPRECENTRIFUGALPCN
 70  5.0        !COPY
 71  -1.0
 72  12.0       !COMPRECENTRIFUGALPCN
 73  -1.0
 74  6.0        !COMPREAXIALPCN
!ARITHY: COMPRETURBINEWORK=COMPREAXIALWORK+COMPRECENTRIFUGALWORK
 75  1.0        !ADD
 76  -1.0
 77  115.0      !COMPRETURBINEWORK
 78  -1.0
 79  101.0      !COMPREAXIALWORK
 80  -1.0
 81  104.0      !COMPRECENTRIFUGALWORK
 -1
 1 2 5.7        !MASS FLOW
 6 6 1500.0     !TET
 -1
                          Time Now 20:51:19
 ************************************************
-1
-1
```

```
6 6 1350.0     !OD CALCULATION: TET = 1350.0K
-1
-1
6 6 1400.0     !OD CALCULATION: TET = 1400.0K
-1
-1
6 6 1450.0
-1
-1
6 6 1500.0
-1
-1
6 6 1550.0
-1
-1
6 6 1600.0
-1
-3
             The Units for this Run are as follows:-
 Temperature = K   Pressure = Atmospheres   Length = metres
 Area = sq metres  Mass Flow = kg/sec       Velocity = metres/sec
 Force = Newtons   s.f.c.(Thrust) =  mg/N sec   s.f.c.(Power) = mug/J
 Sp. Thrust =    N/kg/sec     Power =   Watts
1
     ***** DESIGN POINT ENGINE CALCULATIONS *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 1.0000       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.24510E+01    ETASF =  0.91980E+00    WASF =  0.19204E-01
 Z = 0.85000           PR =   2.500           ETA = 0.79000
 PCN =   1.0000        CN = 1.00000           COMWK =  0.62497E+06
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.15031E-01
 Z = 0.85000           PR =   4.500           ETA = 0.79000
 PCN =   1.0000        CN = 1.00000           COMWK =  0.15385E+07
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000         DLP = 0.5625           WFB =   0.1297
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.10605E+03    ETASF =  0.10249E+01    TFSF =  0.19440E+02
 DHSF =  0.72892E+04
 TF =  401.640         ETA = 0.88000          CN =  2.800
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.74081E-02    ETASF =  0.10609E+01    TFSF =  0.36769E+01
 DHSF =  0.41599E+05
 TF =  219.627         ETA = 0.89000          CN =  2.200
 AUXWK =  0.15670E+07
 Additional Free Turbine Parameters:-
 Speed = 100.0%         Power =  0.15670E+07
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  0.0565         Exit Velocity =  256.97  Gross Thrust =   1458.14
 Nozzle Coeff. =  0.97336E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

 Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
    1   0.00000     5.700   1.00000   1.00000  288.15  288.15     0.0  ******
    2   0.00000     5.700    ******   1.00000  ******  288.15  ******  ******
    3   0.00000     5.700    ******   2.50000  ******  397.01  ******  ******
    4   0.00000     5.700    ******  11.25001  ******  657.58  ******  ******
    5   0.00000     5.204    ******  11.25001  ******  657.58  ******  ******
    6   0.02491     5.334    ******  10.68751  ****** 1500.00  ******  ******
```

```
   7  0.02275    5.830    ******  10.68751  ****** 1434.61  ******  ******
   8  0.02275    5.830    ******   3.31961  ****** 1133.87  ******  ******
   9  0.02275    5.830    ******   3.28641  ****** 1133.87  ******  ******
  10   0.02275    5.830    ******   1.15134  ******  907.76  ******  ******
  11   0.02275    5.830    ******   1.13983  ******  907.76  ******  ******
  12   0.02275    5.830   1.00000   1.13983  879.28  907.76   257.0  0.0565
  13   0.00000    0.496    ******  11.25001  ******  657.58  ******  ******

  Shaft Power =   1567000.00
   Net Thrust =  1458.14
 Equiv. Power =   1661016.50
    Fuel Flow =   0.1297
       S.F.C. =  82.7390
     E.S.F.C. =  78.0558
Sp. Sh. Power =    274912.28
Sp. Eq. Power =    291406.41
Sh. Th. Effy. =   0.2803
         Time Now 20:51:19
*************************************************
-1
6 6 1350.0      !OD CALCULATION: TET = 1350.0K
-1
                                   Time Now 20:51:19
*************************************************
BERR( 1) =    0.00000E+00
BERR( 2) =    0.57027E-01
BERR( 3) =   -0.70144E-01
BERR( 4) =   -0.10641E+00
BERR( 5) =   -0.75515E-01
BERR( 6) =   -0.30568E+00
Loop   1
BERR( 1) =    0.77085E-03
BERR( 2) =    0.41755E-01
BERR( 3) =   -0.51845E-01
BERR( 4) =   -0.79796E-01
BERR( 5) =   -0.50606E-01
BERR( 6) =   -0.21880E+00
Loop   2
BERR( 1) =    0.14842E-02
BERR( 2) =    0.27497E-01
BERR( 3) =   -0.33962E-01
BERR( 4) =   -0.55731E-01
BERR( 5) =   -0.19962E-01
BERR( 6) =   -0.12960E+00
Loop   3
BERR( 1) =    0.19614E-02
BERR( 2) =    0.13345E-01
BERR( 3) =   -0.15493E-01
BERR( 4) =   -0.31668E-01
BERR( 5) =    0.11842E-01
BERR( 6) =   -0.40736E-01
Loop   4
BERR( 1) =    0.15672E-02
BERR( 2) =   -0.96753E-03
BERR( 3) =    0.37332E-02
BERR( 4) =   -0.43027E-02
BERR( 5) =    0.20283E-01
BERR( 6) =    0.23506E-01
Loop   5
BERR( 1) =   -0.11285E-03
BERR( 2) =   -0.44726E-04
BERR( 3) =    0.15079E-02
BERR( 4) =    0.44075E-03
BERR( 5) =   -0.11971E-01
```

```
BERR( 6) =  -0.12464E-01
Loop   6
BERR( 1) =  -0.14696E-05
BERR( 2) =   0.18581E-04
BERR( 3) =   0.35001E-03
BERR( 4) =   0.69256E-04
BERR( 5) =   0.67041E-02
BERR( 6) =   0.66704E-02
Loop   7
BERR( 1) =   0.40636E-05
BERR( 2) =  -0.10196E-05
BERR( 3) =   0.11847E-03
BERR( 4) =  -0.16248E-04
BERR( 5) =  -0.36267E-02
BERR( 6) =  -0.34377E-02
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   7 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0      I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 1.0000       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.24510E+01    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.89995            PR =   2.363            ETA = 0.80554
PCN =   0.9148         CN = 0.91478            COMWK =  0.50058E+06
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.15031E-01
Z = 0.82060            PR =   3.962            ETA = 0.80411
PCN =   0.9148         CN = 0.92590            COMWK =  0.11636E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.4858            WFB =   0.0968
***** TURBINE  1 PARAMETERS *****
CNSF =  0.10605E+03    ETASF =  0.10249E+01    TFSF =  0.19440E+02
DHSF =  0.72892E+04
TF =  401.638          ETA = 0.89049           CN =  2.699
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.74081E-02    ETASF =  0.10609E+01    TFSF =  0.36769E+01
DHSF =  0.41599E+05
TF =  210.281          ETA = 0.84567           CN =  2.318
AUXWK =  0.10720E+07
Additional Free Turbine Parameters:-
Speed = 100.0%          Power =  0.10720E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0565         Exit Velocity =  210.13  Gross Thrust =   1042.33
Nozzle Coeff. =  0.97260E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    5.003   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    5.003    ******   1.00000  ******  288.15  ******  ******
   3  0.00000    5.003    ******   2.36258  ******  387.53  ******  ******
   4  0.00000    5.003    ******   9.35971  ******  613.26  ******  ******
   5  0.00000    4.568    ******   9.35971  ******  613.26  ******  ******
   6  0.02119    4.665    ******   8.87390  ****** 1350.00  ******  ******
   7  0.01935    5.100    ******   8.87390  ****** 1292.23  ******  ******
   8  0.01935    5.100    ******   2.87938  ****** 1021.78  ******  ******
   9  0.01935    5.100    ******   2.85058  ****** 1021.78  ******  ******
  10  0.01935    5.100    ******   1.10380  ******  841.22  ******  ******
  11  0.01935    5.100    ******   1.09276  ******  841.22  ******  ******
  12  0.01935    5.100   1.00000   1.09276  821.87  841.22   210.1  0.0565
  13  0.00000    0.435    ******   9.35971  ******  613.26  ******  ******
```

```
  Shaft Power =   1072012.50
   Net Thrust =  1042.33
 Equiv. Power =   1139218.63
    Fuel Flow =   0.0968
       S.F.C. =  90.3105
     E.S.F.C. =  84.9828
Sp. Sh. Power =    214263.08
Sp. Eq. Power =    227695.56
Sh. Th. Effy. =   0.2568
        Time Now 20:51:19
************************************************
-1
6 6 1400.0      !OD CALCULATION: TET = 1400.0K
-1
                                        Time Now 20:51:20
************************************************
BERR( 1) =    0.40636E-05
BERR( 2) =   -0.18920E-01
BERR( 3) =    0.25799E-01
BERR( 4) =    0.29741E-01
BERR( 5) =    0.55742E-01
BERR( 6) =    0.11265E+00
Loop   1
BERR( 1) =    0.52621E-04
BERR( 2) =   -0.51860E-02
BERR( 3) =    0.79761E-02
BERR( 4) =    0.76329E-02
BERR( 5) =    0.20104E-01
BERR( 6) =    0.34111E-01
Loop   2
BERR( 1) =    0.10847E-03
BERR( 2) =   -0.97266E-04
BERR( 3) =    0.52167E-03
BERR( 4) =   -0.35603E-03
BERR( 5) =    0.46753E-02
BERR( 6) =    0.34385E-02
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 1.0000       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.24510E+01     ETASF =  0.91980E+00     WASF =  0.19204E-01
 Z = 0.88595             PR =   2.409             ETA = 0.80069
 PCN =   0.9408          CN = 0.94077             COMWK =  0.53847E+06
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.34314E+01     ETASF =  0.95181E+00     WASF =  0.15031E-01
 Z = 0.83045             PR =   4.125             ETA = 0.79983
 PCN =   0.9408          CN = 0.94836             COMWK =  0.12731E+07
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000           DLP = 0.5086             WFB =   0.1069
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.10605E+03     ETASF =  0.10249E+01     TFSF =  0.19440E+02
 DHSF =  0.72892E+04
 TF =  401.635           ETA = 0.88767            CN =  2.726
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.74081E-02     ETASF =  0.10609E+01     TFSF =  0.36769E+01
 DHSF =  0.41599E+05
 TF =  212.539           ETA = 0.86288            CN =  2.276
 AUXWK =  0.12210E+07
 Additional Free Turbine Parameters:-
 Speed = 100.0%          Power =  0.12210E+07
```

```
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0565         Exit Velocity =  224.74  Gross Thrust =   1163.91
Nozzle Coeff. =  0.97291E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    5.216   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    5.216   ******   1.00000  ******  288.15  ******  ******
   3  0.00000    5.216   ******   2.40911  ******  390.68  ******  ******
   4  0.00000    5.216   ******   9.93812  ******  627.18  ******  ******
   5  0.00000    4.762   ******   9.93812  ******  627.18  ******  ******
   6  0.02244    4.869   ******   9.42950  ****** 1400.00  ******  ******
   7  0.02049    5.323   ******   9.42950  ****** 1339.61  ******  ******
   8  0.02049    5.323   ******   3.02710  ****** 1059.75  ******  ******
   9  0.02049    5.323   ******   2.99683  ****** 1059.75  ******  ******
  10  0.02049    5.323   ******   1.12318  ******  864.15  ******  ******
  11  0.02049    5.323   ******   1.11195  ******  864.15  ******  ******
  12  0.02049    5.323   1.00000   1.11195  842.15  864.15   224.7  0.0565
  13  0.00000    0.454   ******   9.93812  ******  627.18  ******  ******

  Shaft Power =   1220966.75
   Net Thrust =  1163.91
 Equiv. Power =   1296011.88
    Fuel Flow =   0.1069
       S.F.C. =  87.5245
     E.S.F.C. =  82.4564
Sp. Sh. Power =    234093.19
Sp. Eq. Power =    248481.42
Sh. Th. Effy. =   0.2649
          Time Now 20:51:20
************************************************
-1
6 6 1450.0
-1
                                    Time Now 20:51:20
************************************************
BERR( 1) =    0.10847E-03
BERR( 2) =   -0.18438E-01
BERR( 3) =    0.25353E-01
BERR( 4) =    0.29032E-01
BERR( 5) =    0.36865E-01
BERR( 6) =    0.10952E+00
Loop   1
BERR( 1) =    0.15779E-03
BERR( 2) =   -0.42205E-02
BERR( 3) =    0.65155E-02
BERR( 4) =    0.58863E-02
BERR( 5) =    0.12977E-01
BERR( 6) =    0.27750E-01
Loop   2
BERR( 1) =    0.90219E-04
BERR( 2) =   -0.89508E-04
BERR( 3) =    0.37538E-03
BERR( 4) =   -0.34004E-03
BERR( 5) =    0.33695E-02
BERR( 6) =    0.26053E-02
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =   0.000       Mach No. =  0.00
Etar = 1.0000       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.24510E+01     ETASF =  0.91980E+00     WASF =  0.19204E-01
```

```
Z = 0.87027           PR =   2.454           ETA = 0.79541
PCN =   0.9679        CN = 0.96791           COMWK =  0.57835E+06
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.15031E-01
Z = 0.84042           PR =   4.298           ETA = 0.79536
PCN =   0.9679        CN = 0.97187           COMWK =  0.13924E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000         DLP = 0.5326           WFB =   0.1176
***** TURBINE  1 PARAMETERS *****
CNSF =  0.10605E+03    ETASF =  0.10249E+01    TFSF =  0.19440E+02
DHSF =  0.72892E+04
TF =  401.592          ETA = 0.88445          CN =  2.756
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.74081E-02    ETASF =  0.10609E+01    TFSF =  0.36769E+01
DHSF =  0.41599E+05
TF =  215.204          ETA = 0.87302          CN =  2.236
AUXWK =  0.13803E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.13803E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0565         Exit Velocity =  240.09  Gross Thrust =   1297.79
Nozzle Coeff. =  0.97311E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    5.437   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    5.437   ******   1.00000  ******  288.15  ******  ******
   3  0.00000    5.437   ******   2.45363  ******  393.78  ******  ******
   4  0.00000    5.437   ******  10.54643  ******  641.50  ******  ******
   5  0.00000    4.964   ******  10.54643  ******  641.50  ******  ******
   6  0.02369    5.082   ******  10.01380  ****** 1450.00  ******  ******
   7  0.02163    5.555   ******  10.01380  ****** 1387.05  ******  ******
   8  0.02163    5.555   ******   3.17485  ****** 1097.47  ******  ******
   9  0.02163    5.555   ******   3.14310  ****** 1097.47  ******  ******
  10   0.02163    5.555   ******   1.13529  ******  887.08  ******  ******
  11   0.02163    5.555   ******   1.12394  ******  887.08  ******  ******
  12   0.02163    5.555   1.00000   1.12394  862.15  887.08   240.1  0.0565
  13   0.00000    0.473   ******  10.54643  ******  641.50  ******  ******

  Shaft Power =   1380250.50
   Net Thrust =  1297.79
 Equiv. Power =   1463928.13
    Fuel Flow =   0.1176
       S.F.C. =  85.2080
     E.S.F.C. =  80.3375
Sp. Sh. Power =    253872.86
Sp. Eq. Power =    269263.88
Sh. Th. Effy. =   0.2721
        Time Now 20:51:20
************************************************
-1
6 6 1500.0
-1
                         Time Now 20:51:20
************************************************
BERR( 1) =    0.90219E-04
BERR( 2) =   -0.17893E-01
BERR( 3) =    0.24443E-01
BERR( 4) =    0.28812E-01
BERR( 5) =    0.23202E-01
BERR( 6) =    0.10871E+00
```

```
Loop   1
BERR( 1) =    0.15962E-03
BERR( 2) =   -0.46700E-02
BERR( 3) =    0.73700E-02
BERR( 4) =    0.65676E-02
BERR( 5) =    0.92340E-02
BERR( 6) =    0.31180E-01
Loop   2
BERR( 1) =    0.61612E-04
BERR( 2) =   -0.61294E-04
BERR( 3) =    0.80929E-04
BERR( 4) =   -0.11902E-02
BERR( 5) =    0.34852E-02
BERR( 6) =    0.29616E-02
1
 ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =     0.0     I.S.A. Dev. =    0.000     Mach No. =  0.00
Etar = 1.0000      Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.24510E+01    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.84946            PR =   2.501            ETA = 0.78952
PCN =   1.0008         CN = 1.00075            COMWK =  0.62667E+06
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.15031E-01
Z = 0.84967            PR =   4.503            ETA = 0.78964
PCN =   1.0008         CN = 1.00057            COMWK =  0.15427E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.5638            WFB =   0.1298
***** TURBINE  1 PARAMETERS *****
CNSF =  0.10605E+03    ETASF =  0.10249E+01    TFSF =  0.19440E+02
DHSF =  0.72892E+04
TF =  401.709          ETA = 0.87992           CN =  2.802
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.74081E-02    ETASF =  0.10609E+01    TFSF =  0.36769E+01
DHSF =  0.41599E+05
TF =  219.797          ETA = 0.89057           CN =  2.200
AUXWK =  0.15682E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.15682E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0565         Exit Velocity =  257.27  Gross Thrust =   1461.89
Nozzle Coeff. =  0.97337E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal    Vel   Area
   1  0.00000    5.708   1.00000   1.00000  288.15  288.15    0.0  ******
   2  0.00000    5.708   ******   1.00000  ******  288.15  ******  ******
   3  0.00000    5.708   ******   2.50149  ******  397.16  ******  ******
   4  0.00000    5.708   ******  11.26408  ******  658.06  ******  ******
   5  0.00000    5.212   ******  11.26408  ******  658.06  ******  ******
   6  0.02490    5.341   ******  10.70026  ****** 1500.00  ******  ******
   7  0.02273    5.838   ******  10.70026  ****** 1434.64  ******  ******
   8  0.02273    5.838   ******   3.31723  ****** 1133.48  ******  ******
   9  0.02273    5.838   ******   3.28406  ****** 1133.48  ******  ******
  10  0.02273    5.838   ******   1.15180  ******  907.50  ******  ******
  11  0.02273    5.838   ******   1.14028  ******  907.50  ******  ******
  12  0.02273    5.838   1.00000   1.14028  879.05  907.50   257.3  0.0565
  13  0.00000    0.497   ******  11.26408  ******  658.06  ******  ******

 Shaft Power =   1568211.00
```

```
  Net Thrust =  1461.89
 Equiv. Power =   1662469.38
   Fuel Flow =   0.1298
      S.F.C. =  82.7493
    E.S.F.C. =  78.0576
Sp. Sh. Power =    274749.50
Sp. Eq. Power =    291263.50
Sh. Th. Effy. =   0.2802
        Time Now 20:51:20
*************************************************
-1
6 6 1550.0
-1
                    Time Now 20:51:20
*************************************************
BERR( 1) =    0.61612E-04
BERR( 2) =   -0.17360E-01
BERR( 3) =    0.23234E-01
BERR( 4) =    0.28256E-01
BERR( 5) =    0.57385E-01
BERR( 6) =    0.10728E+00
Loop   1
BERR( 1) =   -0.62489E-03
BERR( 2) =    0.26666E-03
BERR( 3) =   -0.16008E-02
BERR( 4) =   -0.37689E-02
BERR( 5) =    0.60045E-02
BERR( 6) =    0.22978E-02
Loop   2
BERR( 1) =    0.68518E-05
BERR( 2) =   -0.18020E-04
BERR( 3) =    0.50014E-04
BERR( 4) =    0.37940E-03
BERR( 5) =    0.58855E-03
BERR( 6) =    0.63734E-03
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 1.0000       Momentum Drag =       0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.24510E+01     ETASF =  0.91980E+00     WASF =  0.19204E-01
Z = 0.84199             PR =   2.541            ETA = 0.77933
PCN =   1.0173          CN = 1.01726            COMWK =  0.66591E+06
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.34314E+01     ETASF =  0.95181E+00     WASF =  0.15031E-01
Z = 0.85880             PR =   4.632            ETA = 0.78180
PCN =   1.0173          CN = 1.01252            COMWK =  0.16543E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000           DLP = 0.5831            WFB =   0.1404
***** TURBINE  1 PARAMETERS *****
CNSF =  0.10605E+03     ETASF =  0.10249E+01     TFSF =  0.19440E+02
DHSF =  0.72892E+04
TF =  402.103           ETA = 0.88063           CN =  2.802
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.74081E-02     ETASF =  0.10609E+01     TFSF =  0.36769E+01
DHSF =  0.41599E+05
TF =  221.476           ETA = 0.89748           CN =  2.164
AUXWK =  0.17276E+07
Additional Free Turbine Parameters:-
Speed = 100.0%          Power =  0.17276E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
```

NCOSF = 0.10000E+01
Area = 0.0565 Exit Velocity = 271.26 Gross Thrust = 1587.56
Nozzle Coeff. = 0.97352E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers = 1.0000

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	5.871	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	5.871	******	1.00000	******	288.15	******	******
3	0.00000	5.871	******	2.54143	******	400.73	******	******
4	0.00000	5.871	******	11.77235	******	672.23	******	******
5	0.00000	5.361	******	11.77235	******	672.23	******	******
6	0.02619	5.501	******	11.18929	******	1550.00	******	******
7	0.02391	6.012	******	11.18929	******	1482.10	******	******
8	0.02391	6.012	******	3.45199	******	1171.53	******	******
9	0.02391	6.012	******	3.41747	******	1171.53	******	******
10	0.02391	6.012	******	1.16155	******	931.46	******	******
11	0.02391	6.012	******	1.14993	******	931.46	******	******
12	0.02391	6.012	1.00000	1.14993	900.04	931.46	271.3	0.0565
13	0.00000	0.511	******	11.77235	******	672.23	******	******

Shaft Power = 1727610.63
Net Thrust = 1587.56
Equiv. Power = 1829971.88
Fuel Flow = 0.1404
S.F.C. = 81.2723
E.S.F.C. = 76.7263
Sp. Sh. Power = 294243.03
Sp. Eq. Power = 311676.97
Sh. Th. Effy. = 0.2853
Time Now 20:51:20
****
-1
6 6 1600.0
-1
Time Now 20:51:20
****
BERR(1) = 0.68518E-05
BERR(2) = -0.16849E-01
BERR(3) = 0.22124E-01
BERR(4) = 0.29189E-01
BERR(5) = 0.48116E-01
BERR(6) = 0.10091E+00
Loop 1
BERR(1) = 0.23949E-03
BERR(2) = -0.98865E-04
BERR(3) = 0.12631E-02
BERR(4) = -0.94577E-03
BERR(5) = 0.24564E-01
BERR(6) = 0.20837E-02
Loop 2
BERR(1) = -0.73853E-04
BERR(2) = 0.37177E-04
BERR(3) = -0.62912E-03
BERR(4) = 0.24805E-03
BERR(5) = -0.19049E-01
BERR(6) = 0.11651E-02
Loop 3
Loop 4
BERR(1) = 0.51550E-05
BERR(2) = -0.23165E-05
BERR(3) = 0.81980E-04
BERR(4) = -0.24849E-04
BERR(5) = 0.18062E-01
BERR(6) = -0.13770E-02

```
Loop   5
BERR( 1) =    0.10758E-05
BERR( 2) =    0.38584E-06
BERR( 3) =    0.96537E-05
BERR( 4) =   -0.63575E-06
BERR( 5) =    0.38045E-04
BERR( 6) =    0.14080E-04
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   5 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000     Mach No. =  0.00
Etar = 1.0000       Momentum Drag =       0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.24510E+01    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.83411            PR =   2.579            ETA = 0.76980
PCN =   1.0335         CN = 1.03352            COMWK =  0.70495E+06
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.15031E-01
Z = 0.86802            PR =   4.763            ETA = 0.77362
PCN =   1.0335         CN = 1.02435            COMWK =  0.17705E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.6023            WFB =   0.1514
***** TURBINE  1 PARAMETERS *****
CNSF =  0.10605E+03    ETASF =  0.10249E+01    TFSF =  0.19440E+02
DHSF =  0.72892E+04
TF =  402.485          ETA = 0.88133           CN =  2.803
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.74081E-02    ETASF =  0.10609E+01    TFSF =  0.36769E+01
DHSF =  0.41599E+05
TF =  222.700          ETA = 0.90109           CN =  2.130
AUXWK =  0.18846E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.18846E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0565        Exit Velocity =  285.83  Gross Thrust =   1720.90
Nozzle Coeff. =  0.97371E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    6.032   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    6.032    ******   1.00000  ******  288.15  ******  ******
   3  0.00000    6.032    ******   2.57885  ******  404.15  ******  ******
   4  0.00000    6.032    ******  12.28253  ******  686.47  ******  ******
   5  0.00000    5.507    ******  12.28253  ******  686.47  ******  ******
   6  0.02750    5.658    ******  11.68025  ****** 1600.00  ******  ******
   7  0.02511    6.183    ******  11.68025  ****** 1529.57  ******  ******
   8  0.02511    6.183    ******   3.58646  ****** 1209.61  ******  ******
   9  0.02511    6.183    ******   3.55059  ****** 1209.61  ******  ******
  10  0.02511    6.183    ******   1.17408  ******  956.76  ******  ******
  11  0.02511    6.183    ******   1.16234  ******  956.76  ******  ******
  12  0.02511    6.183   1.00000   1.16234  922.12  956.76   285.8  0.0565
  13  0.00000    0.525    ******  12.28253  ******  686.47  ******  ******

 Shaft Power =   1884554.25
  Net Thrust =  1720.90
 Equiv. Power =   1995512.50
   Fuel Flow =   0.1514
      S.F.C. =  80.3620
    E.S.F.C. =  75.8935
Sp. Sh. Power =    312439.25
Sp. Eq. Power =    330834.97
```

```
Sh. Th. Effy. =   0.2886
        Time Now 20:51:20
************************************************
-3
```

A.2 Input and result file for ICR helicopter engine performance simulation

```
 TURBOMATCH SCHEME - Windows NT version (October 1999)
LIMITS:100 Codewords, 800 Brick Data Items, 50 Station Vector
15 BD Items printable by any call of:-
OUTPUT, OUTPBD, OUTPSV, PLOTIT, PLOTBD or PLOTSV
 Input "Program" follows
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!PERFORMANCE SIMULATION OF AN INTERCOOLED/RECUPERATED TWO-SPOOL TURBOSHAFT!
!HELICOPTER ENGINE WITH A FREE POWER TURBINE                              !
!INSPIRED BY TURBOMECCA MAKILA 2A ENGINE CORE    !
!MODELLED BY BARINYIMA NKOI, MARCH 2012
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

OD SI KE CT FP
 -1
 -1
 INTAKE S1-2          D1-4          R100
 COMPRE S2-3          D5-10         R101   V5     V6
 ARITHY               D70-74
 DUCTER S3-4          D11-14
 COMPRE S4-5          D15,6,17-20     R104   V15
 PREMAS S5,6,18       D21-24
 HETCOL S6-7          D25-28
 ARITHY               D75-81
 BURNER S7-8          D29-31        R107
 MIXEES S8,18,9
 TURBIN S9-10         D32-39,115            V33
 DUCTER S10-11        D41-44        R108
 TURBIN S11-12        D45-53                V45    V46
 HETHOT S6,12,16      D54-57
 DUCTER S12-13        D58-61        R110
 NOZCON S13-14,1      D62           R111
 PERFOR S1,0,0        D45,64-66,111,100,107,0,0,0,0,0,0
 CODEND

 !INTAKE
  1  0.0       !ALTITUDE:INLET
  2  0.0       !ISA DEVIATION
  3  0.0       !MACH NO
  4 -1.0       !PRESSURE RECOVERY
!COMPRE AXIAL
  5  0.85      !SURGE MARGIN
  6  -1.0      !ROTATIONAL SPEED
  7  2.5       !PRESSURE RATIO
  8  0.79      !COMPRE EFFICIENCY
  9  0.0       !ERROR SWITCH
 10  2.0       !COMPRE MAP
!DUCTER INTERCOOLER
 11  2.0       !INTERCOOLER
 12  0.04      !PRESSURE LOSS
 13  0.40      !EFFECTIVENESS
 14  100000.0   !LIMITING VALUE OF FUEL FLOW
!COMPRE CENTRIFUGAL
```

```
 15  0.85       !SURGE MARGIN
 16  -1.0       !ROTATIONAL SPEED
 17  4.5        !PRESSURE RATIO
 18  0.79       !COMPRE EFFICIENCY
 19  1.0        !ERROR SWITCH
 20  4.0        !COMPRE MAP
!PREMAS
 21  0.9        !LAMBDA(W) {W5/W4}
 22  0.0        !DELTA(W)
 23  1.0        !LAMBDA(P)
 24  0.0        !DELTA(P)
 !HETCOL
 25  0.01       !COLD SIDE PRESSURE LOSS
 26  0.75       !EFFECTIVENESS
 27  1.0        !TYPE:RECUPERATOR
 28  0.02       !MASS FLOW LEAKAGE
!BURNER
 29  0.05       !PRESSURE LOSS
 30  0.99       !COMBUS EFFICIENCY
 31  -1.0       !FUEL FLOW CALCULATED

 !COMPRE TURBINE
 32  0.0        !COMPRE TURBINE
 33  -1.0       !REL NON-D MASS FLOW
 34  -1.0       !REL NON-D SPEED
 35  0.88       !TURBINE EFFICIENCY
 36  -1.0       !REL ROT SPEED=COMPRE ROT SPEED
 37  2.0        !COMP NO
 38  1.0        !TURBINE MAP
 39  -1.0       !POWER LAW
 !AS IN 115     !COMWRK
!DUCTER
 41  0.0        !DUCTER
 42  0.01       !PRESSURE LOSS
 43  0.0
 44  100000.0
!POWER TURBINE
 45  1567000.0  !POWER TURBINE OUTPUT
 46  -1.0       !REL NON-D MASS FLOW
 47  -1.0       !REL NON-D SPEED
 48  0.89       !TURBINE EFFICIENCY
 49  1.0        !REL ROT SPEED
 50  0.0        !COMP NO
 51  5.0        !TURBINE MAP
 52  1000.0     !POWER LAW INDEX
 53  -1.0       !SET FOR POWER TURBINE
!HETHOT
 54  0.01       !HOT SIDE PRESSURE LOSS
 55  0.75       !EFFECTIVENESS
 56  1.0        !TYPE:RECUPERATOR
 57  0.02       !MASS FLOW LEAKAGE
!DUCTER
 58  0.0        !DUCTER
 59  0.01       !PRESSURE LOSS
 60  0.0
 61  100000.0
!NOZCON
 62  -1.0       !SWITCH TO FIXED AREA
!PERFOR
 !AS IN 48      !POWER TURBINE:POWER OUTPUT
 64  1.0        !PROPELLER EFFICIENCY:PERFORMANCE
 65  0.0        !SCALING INDEX
 66  0.0        !SHAFT POWER
!ARITHY: COMPREAXIALPCN=COMPRECENTRIFUGALPCN
```

```
 70  5.0        !COPY
 71  -1.0
 72  16.0       !COMPRECENTRIFUGALPCN
 73  -1.0
 74  6.0        !COMPREAXIALPCN
!ARITHY: COMPRETURBINEWORK=COMPREAXIALWORK+COMPRECENTRIFUGALWORK
 75  1.0        !ADD
 76  -1.0
 77  115.0      !COMPRETURBINEWORK
 78  -1.0
 79  101.0      !COMPREAXIALWORK
 80  -1.0
 81  104.0      !COMPRECENTRIFUGALWORK
 -1
 1 2 5.7        !MASS FLOW
 4 6 300.0      !INTERCOOLER OUTLET TEMPERATURE
 8 6 1500.0     !TET
 -1
                                Time Now 20:46:34
 ************************************************

              The Units for this Run are as follows:-
 Temperature = K   Pressure = Atmospheres   Length = metres
 Area = sq metres  Mass Flow = kg/sec       Velocity = metres/sec
 Force = Newtons   s.f.c.(Thrust) =  mg/N sec   s.f.c.(Power) = mug/J
 Sp. Thrust =    N/kg/sec     Power =   Watts
1
    ***** DESIGN POINT ENGINE CALCULATIONS *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000       Mach No. =  0.00
 Etar = 1.0000       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.24510E+01    ETASF =  0.91980E+00    WASF =  0.19204E-01
 Z = 0.85000            PR =   2.500            ETA = 0.79000
 PCN =   1.0000         CN = 1.00000            COMWK =  0.62497E+06
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.4000          DLP = 0.1000            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED: 1406.84     KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13611E-01
 Z = 0.85000            PR =   4.500            ETA = 0.79000
 PCN =   1.0000         CN = 1.00000            COMWK =  0.11664E+07
 HETYP =  1.0 HEUA =       6.459
 HETYP =  1.0 HEUA =       7.034
 HETYP =  1.0 HEUA =       7.014
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETAD =  0.75000E+00
 ETA = 0.75000          DLP = 0.1080
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000          DLP = 0.5346            WFB =   0.1040
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.10518E+03    ETASF =  0.10249E+01    TFSF =  0.18590E+02
 DHSF =  0.61204E+04
 TF =  401.640          ETA = 0.88000           CN =  2.800
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.74897E-02    ETASF =  0.10609E+01    TFSF =  0.42488E+01
 DHSF =  0.40432E+05
 TF =  219.627          ETA = 0.89000           CN =  2.200
 AUXWK =  0.15670E+07
 Additional Free Turbine Parameters:-
 Speed = 100.0%         Power =  0.15670E+07
```

```
HETYP =  1.0 HEUA =       7.014
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETAD =  0.75000E+00 HEUA =       7.014 ETASF =  0.00000E+00
ETA =  0.7500          DLP = 0.0137     TOTHOT =   662.2637
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0360         Exit Velocity =  394.50  Gross Thrust =   2235.54
Nozzle Coeff. =  0.97635E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    5.700   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    5.700   ******   1.00000  ******  288.15  ******  ******
   3  0.00000    5.700   ******   2.50000  ******  397.01  ******  ******
   4  0.00000    5.700   ******   2.40000  ******  300.00  ******  ******
   5  0.00000    5.700   ******  10.80001  ******  501.75  ******  ******
   6  0.00000    5.130   ******  10.80001  ******  501.75  ******  ******
   7  0.00000    5.130   ******  10.69201  ******  823.64  ******  ******
   8  0.02028    5.234   ******  10.15741  ****** 1500.00  ******  ******
   9  0.01825    5.804   ******  10.15741  ****** 1410.99  ******  ******
  10  0.01825    5.804   ******   3.85956  ****** 1159.01  ******  ******
  11  0.01825    5.804   ******   3.82096  ****** 1159.01  ******  ******
  12  0.01825    5.804   ******   1.36602  ******  931.24  ******  ******
  13  0.01825    5.804   ******   1.35236  ******  931.24  ******  ******
  14  0.01825    5.804   1.00000   1.35236  863.73  931.24   394.5  0.0360
  15  0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
  16  0.01825    5.804   ******   1.35236  ******  662.26  ******  ******
  17  0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
  18  0.00000    0.570   ******  10.80001  ******  501.75  ******  ******

  Shaft Power =   1567000.00
   Net Thrust =  2235.54
 Equiv. Power =   1711141.13
    Fuel Flow =   0.1040
       S.F.C. =  66.3883
     E.S.F.C. =  60.7960
Sp. Sh. Power =    274912.28
Sp. Eq. Power =    300200.19
Sh. Th. Effy. =  0.3493
         Time Now 20:46:34
***********************************************
-1
8 6 1350.0      !OD CALCULATION: TET = 1350.0K
-1
                              Time Now 20:46:34
***********************************************
BERR( 1) =    0.00000E+00
BERR( 2) =    0.68671E-01
BERR( 3) =   -0.74175E-01
BERR( 4) =   -0.69034E-01
BERR( 5) =   -0.72007E-01
BERR( 6) =   -0.23647E+00
Loop    1
BERR( 1) =   -0.46739E-04
BERR( 2) =    0.47468E-01
BERR( 3) =   -0.51317E-01
BERR( 4) =   -0.48704E-01
BERR( 5) =   -0.42521E-01
BERR( 6) =   -0.16257E+00
Loop    2
BERR( 1) =   -0.11890E-03
BERR( 2) =    0.27906E-01
BERR( 3) =   -0.30120E-01
BERR( 4) =   -0.31385E-01
```

```
 BERR( 5) =   -0.85062E-02
 BERR( 6) =   -0.89792E-01
 Loop   3
 BERR( 1) =    0.34902E-02
 BERR( 2) =    0.95061E-02
 BERR( 3) =   -0.11657E-01
 BERR( 4) =   -0.16997E-01
 BERR( 5) =    0.21180E-01
 BERR( 6) =   -0.23584E-01
 Loop   4
 BERR( 1) =    0.46113E-02
 BERR( 2) =   -0.13412E-02
 BERR( 3) =    0.63934E-03
 BERR( 4) =   -0.44287E-02
 BERR( 5) =    0.17579E-01
 BERR( 6) =    0.72253E-02
 Loop   5
 BERR( 1) =   -0.36238E-03
 BERR( 2) =   -0.17191E-03
 BERR( 3) =    0.95652E-03
 BERR( 4) =    0.12824E-04
 BERR( 5) =   -0.49827E-03
 BERR( 6) =   -0.21723E-02
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   5 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0      I.S.A. Dev. =    0.000       Mach No. =  0.00
 Etar = 1.0000        Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.24510E+01     ETASF =  0.91980E+00     WASF =  0.19204E-01
 Z = 0.92613             PR =   2.370            ETA = 0.79534
 PCN =   0.9031          CN = 0.90308            COMWK =  0.49208E+06
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.4000           DLP = 0.0948            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED: 1097.26      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.34314E+01     ETASF =  0.95181E+00     WASF =  0.13611E-01
 Z = 0.80696             PR =   3.786            ETA = 0.80845
 PCN =   0.9031          CN = 0.90308            COMWK =  0.83345E+06
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.78606           DLP = 0.0913
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000           DLP = 0.4542            WFB =   0.0729
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.10518E+03     ETASF =  0.10249E+01     TFSF =  0.18590E+02
 DHSF =  0.61204E+04
 TF =  402.846           ETA = 0.89641            CN =  2.664
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.74897E-02     ETASF =  0.10609E+01     TFSF =  0.42488E+01
 DHSF =  0.40432E+05
 TF =  211.776           ETA = 0.85340            CN =  2.317
 AUXWK =  0.10616E+07
 Additional Free Turbine Parameters:-
 Speed = 100.0%          Power =  0.10616E+07
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
 ETA =  0.7861           DLP = 0.0100     TOTHOT =   612.6841
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  0.0360          Exit Velocity =  314.88  Gross Thrust =   1505.71
 Nozzle Coeff. =  0.97462E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

```
Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    4.835   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    4.835   ******   1.00000  ******  288.15  ******  ******
   3  0.00000    4.835   ******   2.37035  ******  389.23  ******  ******
   4  0.00000    4.833   ******   2.27554  ******  300.00  ******  ******
   5  0.00000    4.833   ******   8.61532  ******  470.38  ******  ******
   6  0.00000    4.350   ******   8.61532  ******  470.38  ******  ******
   7  0.00000    4.350   ******   8.52405  ******  775.87  ******  ******
   8  0.01676    4.423   ******   8.06985  ****** 1350.00  ******  ******
   9  0.01509    4.906   ******   8.06985  ****** 1270.78  ******  ******
  10   0.01509    4.906   ******   3.21475  ****** 1045.35  ******  ******
  11   0.01509    4.906   ******   3.18260  ****** 1045.35  ******  ******
  12   0.01509    4.906   ******   1.23585  ******  858.99  ******  ******
  13   0.01509    4.906   ******   1.22349  ******  858.99  ******  ******
  14   0.01509    4.906   1.00000   1.22349  815.55  858.99   314.9  0.0360
  15   0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
  16   0.01509    4.906   ******   1.22590  ******  612.68  ******  ******
  17   0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
  18   0.00000    0.483   ******   8.61532  ******  470.38  ******  ******

 Shaft Power =   1061646.63
  Net Thrust =  1505.71
 Equiv. Power =   1158730.25
   Fuel Flow =   0.0729
      S.F.C. =  68.6801
    E.S.F.C. =  62.9257
Sp. Sh. Power =    219568.11
Sp. Eq. Power =    239646.78
Sh. Th. Effy. =   0.3376
        Time Now 20:46:34
************************************************
-1
8 6 1400.0      !OD CALCULATION: TET = 1400.0K
-1
                                        Time Now 20:46:34
************************************************
BERR( 1) =   -0.36238E-03
BERR( 2) =   -0.20901E-01
BERR( 3) =    0.24246E-01
BERR( 4) =    0.16726E-01
BERR( 5) =    0.49380E-01
BERR( 6) =    0.85150E-01
Loop   1
BERR( 1) =    0.28783E-03
BERR( 2) =   -0.75736E-02
BERR( 3) =    0.90537E-02
BERR( 4) =    0.57037E-02
BERR( 5) =    0.22017E-01
BERR( 6) =    0.30764E-01
Loop   2
BERR( 1) =    0.53022E-03
BERR( 2) =   -0.25444E-03
BERR( 3) =    0.40773E-03
BERR( 4) =   -0.36666E-03
BERR( 5) =    0.61747E-02
BERR( 6) =    0.31405E-02
Loop   3
BERR( 1) =   -0.13963E-04
BERR( 2) =    0.65236E-05
BERR( 3) =   -0.15255E-03
BERR( 4) =   -0.30178E-05
BERR( 5) =    0.16762E-03
BERR( 6) =    0.38090E-03
```

```
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =     0.0     I.S.A. Dev. =   0.000      Mach No. =  0.00
Etar = 1.0000      Momentum Drag =     0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.24510E+01    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.90697           PR =   2.421          ETA = 0.79882
PCN =   0.9326        CN = 0.93265          COMWK =  0.53231E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000         DLP = 0.0968          WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1190.52     KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13611E-01
Z = 0.81983           PR =   3.997          ETA = 0.80282
PCN =   0.9326        CN = 0.93265          COMWK =  0.93136E+06
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.77426         DLP = 0.0966
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000         DLP = 0.4807          WFB =   0.0824
***** TURBINE  1 PARAMETERS *****
CNSF =  0.10518E+03    ETASF =  0.10249E+01    TFSF =  0.18590E+02
DHSF =  0.61204E+04
TF =  402.342         ETA = 0.89146         CN =  2.703
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.74897E-02    ETASF =  0.10609E+01    TFSF =  0.42488E+01
DHSF =  0.40432E+05
TF =  213.881         ETA = 0.86890         CN =  2.275
AUXWK =  0.12238E+07
Additional Free Turbine Parameters:-
Speed = 100.0%        Power =  0.12238E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.7743         DLP = 0.0111     TOTHOT =   628.3199
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0360        Exit Velocity =  340.01  Gross Thrust =   1722.36
Nozzle Coeff. =  0.97520E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =    1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal    Vel    Area
   1  0.00000    5.112   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    5.112    ******   1.00000  ******  288.15  ******  ******
   3  0.00000    5.112    ******   2.42088  ******  391.56  ******  ******
   4  0.00000    5.112    ******   2.32404  ******  300.00  ******  ******
   5  0.00000    5.112    ******   9.28882  ******  479.90  ******  ******
   6  0.00000    4.601    ******   9.28882  ******  479.90  ******  ******
   7  0.00000    4.601    ******   9.19222  ****** 791.71  ******  ******
   8  0.01792    4.683    ******   8.71147  ****** 1400.00  ******  ******
   9  0.01613    5.194    ******   8.71147  ****** 1317.43  ******  ******
  10   0.01613    5.194    ******   3.43181  ****** 1084.08  ******  ******
  11   0.01613    5.194    ******   3.39749  ****** 1084.08  ******  ******
  12   0.01613    5.194    ******   1.27693  ******  882.59  ******  ******
  13   0.01613    5.194    ******   1.26416  ******  882.59  ******  ******
  14   0.01613    5.194   1.00000   1.26416  831.81  882.59   340.0  0.0360
  15   0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  16   0.01613    5.194    ******   1.26584  ******  628.32  ******  ******
  17   0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  18   0.00000    0.511    ******   9.28882  ******  479.90  ******  ******

 Shaft Power =   1223804.00
  Net Thrust =  1722.36
```

```
 Equiv. Power =   1334856.50
   Fuel Flow =   0.0824
      S.F.C. =  67.3653
    E.S.F.C. =  61.7609
Sp. Sh. Power =    239398.08
Sp. Eq. Power =    261121.94
Sh. Th. Effy. =   0.3442
         Time Now 20:46:34
**********************************************
-1
8 6 1450.0
-1
                              Time Now 20:46:34
**********************************************
BERR( 1) =   -0.13963E-04
BERR( 2) =   -0.20008E-01
BERR( 3) =    0.22878E-01
BERR( 4) =    0.16830E-01
BERR( 5) =    0.27851E-01
BERR( 6) =    0.76910E-01
Loop   1
BERR( 1) =    0.28044E-02
BERR( 2) =   -0.58148E-02
BERR( 3) =    0.57407E-02
BERR( 4) =    0.33381E-02
BERR( 5) =    0.11947E-01
BERR( 6) =    0.22412E-01
Loop   2
BERR( 1) =    0.22348E-02
BERR( 2) =   -0.17969E-03
BERR( 3) =   -0.69869E-03
BERR( 4) =   -0.13321E-02
BERR( 5) =    0.32634E-02
BERR( 6) =    0.54099E-03
1
   ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000       Mach No. =  0.00
Etar = 1.0000       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.24510E+01     ETASF =  0.91980E+00     WASF =  0.19204E-01
Z = 0.88287             PR =   2.466             ETA = 0.79634
PCN =   0.9644          CN = 0.96440             COMWK =  0.57635E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000           DLP = 0.0986             WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1293.34      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.34314E+01     ETASF =  0.95181E+00     WASF =  0.13611E-01
Z = 0.83226             PR =   4.224             ETA = 0.79678
PCN =   0.9644          CN = 0.96440             COMWK =  0.10401E+07
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.76213           DLP = 0.1024
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000           DLP = 0.5095             WFB =   0.0927
***** TURBINE  1 PARAMETERS *****
CNSF =  0.10518E+03     ETASF =  0.10249E+01     TFSF =  0.18590E+02
DHSF =  0.61204E+04
TF =  402.023           ETA = 0.88630            CN =  2.746
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.74897E-02     ETASF =  0.10609E+01     TFSF =  0.42488E+01
DHSF =  0.40432E+05
```

```
TF =  216.393          ETA = 0.87698          CN =  2.236
AUXWK =  0.13886E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.13886E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.7621          DLP = 0.0124     TOTHOT =  644.9241
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0360         Exit Velocity =  367.14  Gross Thrust =   1968.94
Nozzle Coeff. =  0.97576E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    5.391   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    5.391    ******   1.00000  ******  288.15  ******  ******
   3  0.00000    5.391    ******   2.46557  ******  394.30  ******  ******
   4  0.00000    5.403    ******   2.36694  ******  300.00  ******  ******
   5  0.00000    5.403    ******   9.99699  ******  489.93  ******  ******
   6  0.00000    4.863    ******   9.99699  ******  489.93  ******  ******
   7  0.00000    4.863    ******   9.89461  ******  808.40  ******  ******
   8  0.01907    4.956    ******   9.38510  ****** 1450.00  ******  ******
   9  0.01716    5.496    ******   9.38510  ****** 1364.12  ******  ******
  10   0.01716    5.496    ******   3.64690  ****** 1122.33  ******  ******
  11   0.01716    5.496    ******   3.61043  ****** 1122.33  ******  ******
  12   0.01716    5.496    ******   1.31897  ******  907.76  ******  ******
  13   0.01716    5.496    ******   1.30578  ******  907.76  ******  ******
  14   0.01716    5.496   1.00000   1.30578  848.87  907.76   367.1  0.0360
  15   0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  16   0.01716    5.496    ******   1.30661  ******  644.92  ******  ******
  17   0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  18   0.00000    0.540    ******   9.99699  ******  489.93  ******  ******

  Shaft Power =   1388630.38
   Net Thrust =  1968.94
 Equiv. Power =   1515582.00
    Fuel Flow =   0.0927
       S.F.C. =  66.7848
     E.S.F.C. =  61.1907
Sp. Sh. Power =    257569.69
Sp. Eq. Power =    281117.28
Sh. Th. Effy. =   0.3472
          Time Now 20:46:34
************************************************
-1
8 6 1500.0
-1
                              Time Now 20:46:34
************************************************
BERR( 1) =    0.22348E-02
BERR( 2) =   -0.19524E-01
BERR( 3) =    0.21887E-01
BERR( 4) =    0.15723E-01
BERR( 5) =    0.15824E-01
BERR( 6) =    0.78358E-01
Loop   1
BERR( 1) =    0.23979E-03
BERR( 2) =   -0.44476E-02
BERR( 3) =    0.59806E-02
BERR( 4) =    0.29420E-02
BERR( 5) =    0.61762E-02
BERR( 6) =    0.19060E-01
Loop   2
BERR( 1) =   -0.12270E-03
BERR( 2) =   -0.16622E-03
```

```
 BERR( 3) =    0.49361E-03
 BERR( 4) =   -0.34231E-03
 BERR( 5) =    0.19047E-02
 BERR( 6) =    0.16291E-02
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 1.0000       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.24510E+01    ETASF =  0.91980E+00    WASF =  0.19204E-01
 Z = 0.84843            PR =   2.497            ETA = 0.79002
 PCN =   0.9999         CN = 0.99987            COMWK =  0.62417E+06
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.4000          DLP = 0.0999            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED: 1404.77      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13611E-01
 Z = 0.84439            PR =   4.476            ETA = 0.79002
 PCN =   0.9999         CN = 0.99987            COMWK =  0.11615E+07
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.74998          DLP = 0.1086
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000          DLP = 0.5387            WFB =   0.1040
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.10518E+03    ETASF =  0.10249E+01    TFSF =  0.18590E+02
 DHSF =  0.61204E+04
 TF =  401.970          ETA = 0.88065           CN =  2.800
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.74897E-02    ETASF =  0.10609E+01    TFSF =  0.42488E+01
 DHSF =  0.40432E+05
 TF =  220.420          ETA = 0.89285           CN =  2.199
 AUXWK =  0.15681E+07
 Additional Free Turbine Parameters:-
 Speed = 100.0%         Power =  0.15681E+07
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
 ETA =  0.7500          DLP = 0.0137     TOTHOT =   661.7667
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  0.0360         Exit Velocity =  394.76  Gross Thrust =   2237.33
 Nozzle Coeff. =  0.97636E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

 Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
    1  0.00000    5.702   1.00000   1.00000  288.15  288.15     0.0  ******
    2  0.00000    5.702   ******   1.00000  ******  288.15  ******  ******
    3  0.00000    5.702   ******   2.49691  ******  396.84  ******  ******
    4  0.00000    5.701   ******   2.39703  ******  300.00  ******  ******
    5  0.00000    5.701   ******  10.72958  ******  500.88  ******  ******
    6  0.00000    5.131   ******  10.72958  ******  500.88  ******  ******
    7  0.00000    5.131   ******  10.62102  ******  824.17  ******  ******
    8  0.02026    5.235   ******  10.08235  ****** 1500.00  ******  ******
    9  0.01824    5.805   ******  10.08235  ****** 1410.91  ******  ******
   10  0.01824    5.805   ******   3.84777  ****** 1159.78  ******  ******
   11  0.01824    5.805   ******   3.80929  ****** 1159.78  ******  ******
   12  0.01824    5.805   ******   1.36714  ******  931.91  ******  ******
   13  0.01824    5.805   ******   1.35347  ******  931.91  ******  ******
   14  0.01824    5.805   1.00000   1.35347  864.16  931.91   394.8  0.0360
   15  0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
   16  0.01824    5.805   ******   1.35348  ******  661.77  ******  ******
   17  0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
```

```
  18   0.00000    0.570    ******  10.72958  ******  500.88  ******  ******

  Shaft Power =   1568067.63
   Net Thrust =  2237.33
 Equiv. Power =   1712323.63
    Fuel Flow =   0.1040
       S.F.C. =  66.3045
     E.S.F.C. =  60.7186
Sp. Sh. Power =    275024.06
Sp. Eq. Power =    300325.19
Sh. Th. Effy. =   0.3497
         Time Now 20:46:34
************************************************
-1
8 6 1550.0
-1
                                         Time Now 20:46:34
************************************************
BERR( 1) =   -0.12270E-03
BERR( 2) =   -0.18892E-01
BERR( 3) =    0.22398E-01
BERR( 4) =    0.17176E-01
BERR( 5) =    0.51480E-01
BERR( 6) =    0.76078E-01
Loop   1
BERR( 1) =    0.89397E-02
BERR( 2) =   -0.11724E-02
BERR( 3) =   -0.19656E-01
BERR( 4) =   -0.20658E-01
BERR( 5) =    0.19951E-01
BERR( 6) =    0.54000E-02
Loop   2
BERR( 1) =   -0.56232E-02
BERR( 2) =    0.41130E-03
BERR( 3) =    0.13225E-01
BERR( 4) =    0.13530E-01
BERR( 5) =   -0.79368E-02
BERR( 6) =    0.41347E-03
Loop   3
BERR( 1) =    0.36921E-02
BERR( 2) =   -0.26529E-03
BERR( 3) =   -0.84556E-02
BERR( 4) =   -0.87518E-02
BERR( 5) =    0.56589E-02
BERR( 6) =    0.63832E-03
Loop   4
BERR( 1) =   -0.23366E-02
BERR( 2) =    0.17332E-03
BERR( 3) =    0.54472E-02
BERR( 4) =    0.55915E-02
BERR( 5) =   -0.34953E-02
BERR( 6) =   -0.10100E-03
Loop   5
BERR( 1) =    0.15165E-02
BERR( 2) =   -0.11071E-03
BERR( 3) =   -0.34962E-02
BERR( 4) =   -0.36067E-02
BERR( 5) =    0.22959E-02
BERR( 6) =    0.19408E-03
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   5 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000       Mach No. =  0.00
Etar = 1.0000       Momentum Drag =      0.00
```

```
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.24510E+01    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.82918            PR =   2.521            ETA = 0.77914
PCN =   1.0183         CN = 1.01831            COMWK =  0.66281E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000          DLP = 0.1009            WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1496.38     KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13611E-01
Z = 0.85730            PR =   4.670            ETA = 0.77807
PCN =   1.0183         CN = 1.01831            COMWK =  0.12651E+07
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.74160          DLP = 0.1129
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.5621            WFB =   0.1137
***** TURBINE  1 PARAMETERS *****
CNSF =  0.10518E+03    ETASF =  0.10249E+01    TFSF =  0.18590E+02
DHSF =  0.61204E+04
TF =  402.114          ETA = 0.88035           CN =  2.805
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.74897E-02    ETASF =  0.10609E+01    TFSF =  0.42488E+01
DHSF =  0.40432E+05
TF =  221.407          ETA = 0.89725           CN =  2.164
AUXWK =  0.17156E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.17156E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.7416          DLP = 0.0147     TOTHOT =   679.3574
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0360         Exit Velocity =  418.74  Gross Thrust =   2463.39
Nozzle Coeff. =  0.97682E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	5.900	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	5.900	******	1.00000	******	288.15	******	******
3	0.00000	5.900	******	2.52132	******	399.68	******	******
4	0.00000	5.909	******	2.42047	******	300.00	******	******
5	0.00000	5.909	******	11.30386	******	510.93	******	******
6	0.00000	5.318	******	11.30386	******	510.93	******	******
7	0.00000	5.318	******	11.19095	******	843.51	******	******
8	0.02137	5.432	******	10.62884	******	1550.00	******	******
9	0.01923	6.022	******	10.62884	******	1457.63	******	******
10	0.01923	6.022	******	4.02603	******	1198.03	******	******
11	0.01923	6.022	******	3.98577	******	1198.03	******	******
12	0.01923	6.022	******	1.40551	******	959.35	******	******
13	0.01923	6.022	******	1.39146	******	959.35	******	******
14	0.01923	6.022	1.00000	1.39146	883.55	959.35	418.7	0.0360
15	0.00000	0.000	******	0.00000	******	0.00	******	******
16	0.01923	6.022	******	1.39079	******	679.36	******	******
17	0.00000	0.000	******	0.00000	******	0.00	******	******
18	0.00000	0.591	******	11.30386	******	510.93	******	******

```
 Shaft Power =   1715589.88
  Net Thrust =  2463.39
 Equiv. Power =   1874421.63
   Fuel Flow =   0.1137
      S.F.C. =  66.2480
    E.S.F.C. =  60.6344
Sp. Sh. Power =    290786.72
```

```
Sp. Eq. Power =    317708.19
Sh. Th. Effy. =  0.3500
       Time Now 20:46:34
**********************************************
-1
8 6 1600.0
-1
                                  Time Now 20:46:34
**********************************************
BERR( 1) =    0.15165E-02
BERR( 2) =   -0.18265E-01
BERR( 3) =    0.17510E-01
BERR( 4) =    0.13679E-01
BERR( 5) =    0.46182E-01
BERR( 6) =    0.70511E-01
Loop   1
BERR( 1) =    0.17442E-03
BERR( 2) =   -0.19708E-03
BERR( 3) =    0.10086E-02
BERR( 4) =   -0.80552E-03
BERR( 5) =    0.52657E-02
BERR( 6) =    0.14553E-02
Loop   2
BERR( 1) =    0.17855E-05
BERR( 2) =    0.54984E-05
BERR( 3) =   -0.20037E-03
BERR( 4) =    0.36431E-05
BERR( 5) =   -0.15187E-02
BERR( 6) =    0.19780E-03
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 1.0000       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.24510E+01     ETASF =  0.91980E+00     WASF =  0.19204E-01
Z = 0.81137             PR =   2.534            ETA = 0.77169
PCN =   1.0328          CN = 1.03285            COMWK =  0.69119E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000           DLP = 0.1013            WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1563.31      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.34314E+01     ETASF =  0.95181E+00     WASF =  0.13611E-01
Z = 0.87008             PR =   4.838            ETA = 0.76778
PCN =   1.0328          CN = 1.03285            COMWK =  0.13514E+07
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.73568           DLP = 0.1159
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000           DLP = 0.5815            WFB =   0.1223
***** TURBINE  1 PARAMETERS *****
CNSF =  0.10518E+03     ETASF =  0.10249E+01     TFSF =  0.18590E+02
DHSF =  0.61204E+04
TF =  402.495           ETA = 0.88153           CN =  2.801
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.74897E-02     ETASF =  0.10609E+01     TFSF =  0.42488E+01
DHSF =  0.40432E+05
TF =  222.203           ETA = 0.89983           CN =  2.129
AUXWK =  0.18519E+07
Additional Free Turbine Parameters:-
Speed = 100.0%          Power =  0.18519E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
```

```
ETA =  0.7357          DLP = 0.0156     TOTHOT =   696.8683
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0360          Exit Velocity =  440.19  Gross Thrust =   2658.12
Nozzle Coeff. =  0.97722E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    6.057   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    6.057    ******   1.00000  ******  288.15  ******  ******
   3  0.00000    6.057    ******   2.53373  ******  401.42  ******  ******
   4  0.00000    6.057    ******   2.43238  ******  300.00  ******  ******
   5  0.00000    6.057    ******  11.76695  ******  519.67  ******  ******
   6  0.00000    5.451    ******  11.76695  ******  519.67  ******  ******
   7  0.00000    5.451    ******  11.65102  ******  864.62  ******  ******
   8  0.02244    5.574    ******  11.06949  ****** 1600.00  ******  ******
   9  0.02020    6.179    ******  11.06949  ****** 1504.24  ******  ******
  10  0.02020    6.179    ******   4.19920  ****** 1237.90  ******  ******
  11  0.02020    6.179    ******   4.15721  ****** 1237.90  ******  ******
  12  0.02020    6.179    ******   1.44103  ******  988.51  ******  ******
  13  0.02020    6.179    ******   1.42662  ******  988.51  ******  ******
  14  0.02020    6.179   1.00000   1.42662  905.23  988.51   440.2  0.0360
  15  0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  16  0.02020    6.179    ******   1.42545  ******  696.87  ******  ******
  17  0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  18  0.00000    0.606    ******  11.76695  ******  519.67  ******  ******

  Shaft Power =   1851885.00
   Net Thrust =  2658.12
 Equiv. Power =   2023272.25
    Fuel Flow =   0.1223
       S.F.C. =  66.0677
     E.S.F.C. =  60.4712
Sp. Sh. Power =    305745.41
Sp. Eq. Power =    334041.38
Sh. Th. Effy. =   0.3510
        Time Now 20:46:34
*****************************************************
-3
```

A.3 Input and result file for LPC-ZS helicopter engine performance simulation

```
TURBOMATCH SCHEME - Windows NT version (October 1999)
 LIMITS:100 Codewords, 800 Brick Data Items, 50 Station Vector
 15 BD Items printable by any call of:-
 OUTPUT, OUTPBD, OUTPSV, PLOTIT, PLOTBD or PLOTSV
  Input "Program" follows
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!PERFORMANCE SIMULATION OF A TWO-SPOOL TURBOSHAFT!

!HELICOPTER ENGINE WITH A FREE POWER TURBINE AND !

!ZEROSTAGED LP COMPRESSOR                    !

!INSPIRED BY TURBOMECCA MAKILA 2A ENGINE CORE    !

!MODELLED BY BARINYIMA NKOI, MARCH 2012          !

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

```
OD SI KE CT FP
 -1
 -1
 INTAKE S1-2            D1-4            R100
 COMPRE S2-3            D5-10           R101   V5     V6
 COMPRE S3-4            D11,6,13-16     R102   V11
 ARITHY                 D70-74
 ARITHY                 D75-81
 COMPRE S4-5            D17,6,19-22     R104   V17
 PREMAS S5,6,14         D23-26
 ARITHY                 D82-88
 BURNER S6-7            D27-29          R107
 MIXEES S7,14,8
 TURBIN S8-9            D30-37,120             V31
 DUCTER S9-10           D39-42          R108
 TURBIN S10-11          D43-51                 V43    V44
 DUCTER S11-12          D52-55          R110
 NOZCON S12-13,1        D56             R111
 PERFOR S1,0,0          D43,58-60,111,100,107,0,0,0,0,0,0
 CODEND

!INTAKE
  1  0.0        !ALTITUDE:INLET
  2  0.0        !ISA DEVIATION
  3  0.0        !MACH NO
  4 -1.0        !PRESSURE RECOVERY
!COMPRE ZEROSTAGE
  5  0.85       !SURGE MARGIN
  6  -1.0       !ROTATIONAL SPEED
  7  1.13       !PRESSURE RATIO
  8  0.79       !COMPRE EFFICIENCY
  9  0.0        !ERROR SWITCH
 10  2.0        !COMPRE MAP
!COMPRE AXIAL
 11  0.85       !SURGE MARGIN
 !PCN AS IN 6   !ROTATIONAL SPEED
 13  2.5        !PRESSURE RATIO
 14  0.79       !COMPRE EFFICIENCY
 15  0.0        !ERROR SWITCH
 16  4.0        !COMPRE MAP
!COMPRE CENTRIFUGAL
 17  0.85       !SURGE MARGIN
 18  -1.0       !ROTATIONAL SPEED
 19  4.5        !PRESSURE RATIO
 20  0.79       !COMPRE EFFICIENCY
 21  1.0        !ERROR SWITCH
 22  4.0        !COMPRE MAP
!PREMAS
 23  0.919      !LAMBDA(W) {W5/W4}
 24  0.0        !DELTA(W)
 25  1.0        !LAMBDA(P)
 26  0.0        !DELTA(P)
!BURNER
 27  0.05       !PRESSURE LOSS
 28  0.99       !COMBUS EFFICIENCY
 29  -1.0       !FUEL FLOW CALCULATED
!COMPRE TURBINE
 30  0.0        !COMPRE TURBINE
 31  -1.0       !REL NON-D MASS FLOW
 32  -1.0       !REL NON-D SPEED
 33  0.88       !TURBINE EFFICIENCY
 34  -1.0       !REL ROT SPEED=COMPRE ROT SPEED
 35  2.0        !COMP NO
 36  4.0        !TURBINE MAP
```

```
 37  -1.0        !POWER LAW
 !AS IN 120      !COMWRK
!DUCTER
 39  0.0         !DUCTER
 40  0.01         !PRESSURE LOSS
 41  0.0
 42  100000.0
!POWER TURBINE
 43  1567000.0   !POWER TURBINE output
 44  -1.0        !REL NON-D MASS FLOW
 45  -1.0        !REL NON-D SPEED
 46  0.89         !TURBINE EFFICIENCY
 47  1.0         !REL ROT SPEED
 48  0.0         !COMP NO
 49  5.0         !TURBINE MAP
 50  1000.0       !POWER LAW INDEX
 51  -1.0        !SET FOR POWER TURBINE
!DUCTER
 52  0.0         !DUCTER
 53  0.01         !PRESSURE LOSS
 54  0.0
 55  100000.0
!NOZCON
 56  -1.0        !SWITCH TO FIXED AREA
!PERFOR
 !AS IN 48       !POWER TURBINE:POWER OUTPUT
 58  1.0         !PROPELLER EFFICIENCY:PERFORMANCE
 59  0.0         !SCALING INDEX
 60  0.0         !SHAFT POWER
!ARITHY: COMPREAXIALPCN=COMPRECENTRIFUGALPCN
 70  5.0         !COPY
 71  -1.0
 72  18.0         !COMPRECENTRIFUGALPCN
 73  -1.0
 74  6.0         !COMPREAXIALPCN
!ARITHY: COMPREWORK1=COMPREAXIALWORK+COMPREZEROSTAGEWORK
 75  1.0         !ADD
 76  -1.0
 77  115.0        !COMPREWORK1
 78  -1.0
 79  101.0        !COMPREZEROSTAGEWORK
 80  -1.0
 81  102.0        !COMPREAXIALWORK
!ARITHY: COMPRETURBINEWORK=COMPREWORK1+COMPRECENTRIFUGALWORK
 82  1.0         !ADD
 83  -1.0
 84  120.0        !COMPRETURBINEWORK
 85  -1.0
 86  115.0        !COMPREWORK1
 87  -1.0
 88  104.0        !COMPRECENTRIFUGALWORK
 -1
 1 2 5.7         !MASS FLOW
 7 6 1500.0      !TET
 -1
                         Time Now 20:54:30

 ***********************************************
              The Units for this Run are as follows:-
 Temperature = K   Pressure = Atmospheres   Length = metres
 Area = sq metres  Mass Flow = kg/sec       Velocity = metres/sec
 Force = Newtons   s.f.c.(Thrust) =  mg/N sec   s.f.c.(Power) = mug/J
 Sp. Thrust =    N/kg/sec     Power =   Watts
1
```

```
     ***** DESIGN POINT ENGINE CALCULATIONS *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 1.0000       Momentum Drag =       0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.21242E+00    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.85000            PR =   1.130            ETA = 0.79000
PCN =   1.0000         CN = 1.00000            COMWK =  0.74218E+05
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.14706E+01    ETASF =  0.95181E+00    WASF =  0.28962E-01
Z = 0.85000            PR =   2.500            ETA = 0.79000
PCN =   1.0000         CN = 1.00000            COMWK =  0.65302E+06
***** COMPRESSOR  3 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13595E-01
Z = 0.85000            PR =   4.500            ETA = 0.79000
PCN =   1.0000         CN = 1.00000            COMWK =  0.16058E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.6356            WFB =   0.1265
***** TURBINE  1 PARAMETERS *****
CNSF =  0.78196E+02    ETASF =  0.10332E+01    TFSF =  0.22625E+02
DHSF =  0.16249E+05
TF =  414.346          ETA = 0.88000           CN =  2.060
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.73490E-02    ETASF =  0.10609E+01    TFSF =  0.37873E+01
DHSF =  0.42293E+05
TF =  219.627          ETA = 0.89000           CN =  2.200
AUXWK =  0.15670E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.15670E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0557         Exit Velocity =  254.84  Gross Thrust =   1445.28
Nozzle Coeff. =  0.97337E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	5.700	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	5.700	******	1.00000	******	288.15	******	******
3	0.00000	5.700	******	1.13000	******	301.12	******	******
4	0.00000	5.700	******	2.82500	******	414.71	******	******
5	0.00000	5.700	******	12.71251	******	685.45	******	******
6	0.00000	5.238	******	12.71251	******	685.45	******	******
7	0.02415	5.365	******	12.07688	******	1500.00	******	******
8	0.02219	5.826	******	12.07688	******	1440.92	******	******
9	0.02219	5.826	******	3.39015	******	1115.86	******	******
10	0.02219	5.826	******	3.35625	******	1115.86	******	******
11	0.02219	5.826	******	1.15185	******	888.68	******	******
12	0.02219	5.826	******	1.14033	******	888.68	******	******
13	0.02219	5.826	1.00000	1.14033	860.54	888.68	254.8	0.0557
14	0.00000	0.462	******	12.71251	******	685.45	******	******

```
  Shaft Power =   1567000.00
   Net Thrust =  1445.28
 Equiv. Power =   1660187.13
    Fuel Flow =   0.1265
       S.F.C. =  80.7230
     E.S.F.C. =  76.1920
Sp. Sh. Power =    274912.28
Sp. Eq. Power =    291260.91
Sh. Th. Effy. =   0.2873
        Time Now 20:54:30
************************************************
```

```
-1
7 6 1350.0
-1
                                        Time Now 20:54:30
***************************************************
BERR( 1) =    0.00000E+00
BERR( 2) =    0.00000E+00
BERR( 3) =    0.57076E-01
BERR( 4) =   -0.92976E-01
BERR( 5) =   -0.84233E-01
BERR( 6) =   -0.80430E-01
BERR( 7) =   -0.29854E+00
Loop   1
BERR( 1) =    0.10225E-04
BERR( 2) =    0.89155E-03
BERR( 3) =    0.42840E-01
BERR( 4) =   -0.70255E-01
BERR( 5) =   -0.65051E-01
BERR( 6) =   -0.55906E-01
BERR( 7) =   -0.21972E+00
Loop   2
BERR( 1) =   -0.27316E-03
BERR( 2) =    0.17697E-02
BERR( 3) =    0.29664E-01
BERR( 4) =   -0.47772E-01
BERR( 5) =   -0.46959E-01
BERR( 6) =   -0.25899E-01
BERR( 7) =   -0.13918E+00
Loop   3
BERR( 1) =   -0.16937E-03
BERR( 2) =    0.24465E-02
BERR( 3) =    0.17129E-01
BERR( 4) =   -0.25559E-01
BERR( 5) =   -0.29279E-01
BERR( 6) =    0.52606E-02
BERR( 7) =   -0.60858E-01
Loop   4
BERR( 1) =    0.18343E-02
BERR( 2) =    0.29524E-02
BERR( 3) =    0.43975E-02
BERR( 4) =   -0.44105E-02
BERR( 5) =   -0.10806E-01
BERR( 6) =    0.25297E-01
BERR( 7) =    0.57827E-02
Loop   5
BERR( 1) =   -0.17797E-02
BERR( 2) =    0.11436E-02
BERR( 3) =   -0.13310E-03
BERR( 4) =    0.78223E-03
BERR( 5) =   -0.58919E-03
BERR( 6) =   -0.80553E-03
BERR( 7) =    0.71838E-03
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   5 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =     0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 1.0000       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.21242E+00    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.91938            PR =   1.117            ETA = 0.80023
PCN =   0.8987         CN = 0.89872             COMWK =  0.56054E+05
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.14706E+01    ETASF =  0.95181E+00    WASF =  0.28962E-01
Z = 0.91341            PR =   2.345            ETA = 0.80322
```

```
PCN =   0.8987        CN = 0.90082          COMWK =  0.49814E+06
***** COMPRESSOR  3 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13595E-01
Z = 0.82764           PR =   3.911          ETA = 0.80666
PCN =   0.8987        CN = 0.91250          COMWK =  0.11474E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000         DLP = 0.5213          WFB =   0.0917
***** TURBINE  1 PARAMETERS *****
CNSF =  0.78196E+02    ETASF =  0.10332E+01    TFSF =  0.22625E+02
DHSF =  0.16249E+05
TF =  411.996         ETA = 0.87424         CN =  1.951
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.73490E-02    ETASF =  0.10609E+01    TFSF =  0.37873E+01
DHSF =  0.42293E+05
TF =  209.157         ETA = 0.84129         CN =  2.312
AUXWK =  0.10094E+07
Additional Free Turbine Parameters:-
Speed = 100.0%        Power =  0.10094E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0557        Exit Velocity =  203.74  Gross Thrust =    974.25
Nozzle Coeff. =  0.97259E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    4.828   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    4.828    ******   1.00000  ******  288.15  ******  ******
   3  0.00000    4.819    ******   1.11692  ******  299.72  ******  ******
   4  0.00000    4.825    ******   2.61969  ******  402.27  ******  ******
   5  0.00000    4.825    ******  10.24548  ******  632.36  ******  ******
   6  0.00000    4.434    ******  10.24548  ******  632.36  ******  ******
   7  0.02068    4.526    ******   9.72415  ****** 1350.00  ******  ******
   8  0.01901    4.917    ******   9.72415  ****** 1297.48  ******  ******
   9  0.01901    4.917    ******   2.85664  ****** 1010.32  ******  ******
  10  0.01901    4.917    ******   2.82807  ****** 1010.32  ******  ******
  11  0.01901    4.917    ******   1.10315  ******  833.56  ******  ******
  12  0.01901    4.917    ******   1.09212  ******  833.56  ******  ******
  13  0.01901    4.917   1.00000   1.09212  815.32  833.56   203.7  0.0557
  14  0.00000    0.391    ******  10.24548  ******  632.36  ******  ******

 Shaft Power =   1009374.00
  Net Thrust =   974.25
 Equiv. Power =   1072190.50
   Fuel Flow =   0.0917
     S.F.C. =  90.8523
   E.S.F.C. =  85.5295
Sp. Sh. Power =   209070.31
Sp. Eq. Power =   222081.42
Sh. Th. Effy. =  0.2552
       Time Now 20:54:30
************************************************
-1
7 6 1400.0
-1
                              Time Now 20:54:30
************************************************
BERR( 1) =   -0.17797E-02
BERR( 2) =    0.11436E-02
BERR( 3) =   -0.19073E-01
BERR( 4) =    0.33667E-01
BERR( 5) =    0.22520E-01
BERR( 6) =    0.60732E-01
```

```
BERR( 7) =   0.11170E+00
Loop   1
BERR( 1) =  -0.15154E-02
BERR( 2) =   0.85376E-03
BERR( 3) =  -0.82011E-02
BERR( 4) =   0.14829E-01
BERR( 5) =   0.92826E-02
BERR( 6) =   0.31096E-01
BERR( 7) =   0.51119E-01
Loop   2
BERR( 1) =  -0.13289E-02
BERR( 2) =   0.12648E-02
BERR( 3) =   0.44560E-03
BERR( 4) =  -0.41284E-04
BERR( 5) =  -0.13097E-02
BERR( 6) =   0.80273E-02
BERR( 7) =   0.24942E-02
Loop   3
BERR( 1) =  -0.58028E-03
BERR( 2) =   0.31874E-04
BERR( 3) =   0.35410E-05
BERR( 4) =  -0.71898E-04
BERR( 5) =  -0.87689E-04
BERR( 6) =   0.35473E-03
BERR( 7) =  -0.23564E-03
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =     0.0     I.S.A. Dev. =   0.000     Mach No. =  0.00
Etar = 1.0000      Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.21242E+00    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.90218            PR =   1.122            ETA = 0.80162
PCN =   0.9298         CN = 0.92982            COMWK =  0.61568E+05
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.14706E+01    ETASF =  0.95181E+00    WASF =  0.28962E-01
Z = 0.89567            PR =   2.400            ETA = 0.80231
PCN =   0.9298         CN = 0.93130            COMWK =  0.54482E+06
***** COMPRESSOR  3 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13595E-01
Z = 0.83603            PR =   4.096            ETA = 0.80149
PCN =   0.9298         CN = 0.93965            COMWK =  0.12833E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.5560            WFB =   0.1025
***** TURBINE  1 PARAMETERS *****
CNSF =  0.78196E+02    ETASF =  0.10332E+01    TFSF =  0.22625E+02
DHSF =  0.16249E+05
TF =  412.529          ETA = 0.87621           CN =  1.982
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.73490E-02    ETASF =  0.10609E+01    TFSF =  0.37873E+01
DHSF =  0.42293E+05
TF =  211.889          ETA = 0.86036           CN =  2.272
AUXWK =  0.11865E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.11865E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0557         Exit Velocity =  219.65  Gross Thrust =   1112.27
Nozzle Coeff. =  0.97279E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
```

```
   1  0.00000    5.106   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    5.106   ******   1.00000  ******  288.15  ******  ******
   3  0.00000    5.103   ******   1.12184  ******  300.17  ******  ******
   4  0.00000    5.103   ******   2.69199  ******  406.07  ******  ******
   5  0.00000    5.103   ******  11.02694  ******  648.89  ******  ******
   6  0.00000    4.690   ******  11.02694  ******  648.89  ******  ******
   7  0.02185    4.792   ******  10.47095  ****** 1400.00  ******  ******
   8  0.02008    5.205   ******  10.47095  ****** 1345.21  ******  ******
   9  0.02008    5.205   ******   3.03966  ****** 1046.28  ******  ******
  10  0.02008    5.205   ******   3.00927  ****** 1046.28  ******  ******
  11  0.02008    5.205   ******   1.11556  ******  851.30  ******  ******
  12  0.02008    5.205   ******   1.10441  ******  851.30  ******  ******
  13  0.02008    5.205   1.00000   1.10441  830.22  851.30   219.7  0.0557
  14  0.00000    0.413   ******  11.02694  ******  648.89  ******  ******

  Shaft Power =   1186543.50
   Net Thrust =  1112.27
 Equiv. Power =   1258259.13
    Fuel Flow =   0.1025
       S.F.C. =  86.3661
     E.S.F.C. =  81.4436
Sp. Sh. Power =    232395.27
Sp. Eq. Power =    246441.42
Sh. Th. Effy. =   0.2685
        Time Now 20:54:30
************************************************
-1
7 6 1450.0
-1
                              Time Now 20:54:30
************************************************
BERR( 1) =   -0.58028E-03
BERR( 2) =    0.31874E-04
BERR( 3) =   -0.18360E-01
BERR( 4) =    0.31646E-01
BERR( 5) =    0.22744E-01
BERR( 6) =    0.32303E-01
BERR( 7) =    0.10146E+00
Loop   1
BERR( 1) =   -0.89005E-03
BERR( 2) =    0.23729E-03
BERR( 3) =   -0.59944E-02
BERR( 4) =    0.10866E-01
BERR( 5) =    0.71180E-02
BERR( 6) =    0.14673E-01
BERR( 7) =    0.34973E-01
Loop   2
BERR( 1) =   -0.33821E-03
BERR( 2) =    0.22919E-03
BERR( 3) =    0.21950E-04
BERR( 4) =   -0.12397E-03
BERR( 5) =   -0.97024E-03
BERR( 6) =    0.47947E-02
BERR( 7) =    0.17298E-02
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =   0.000     Mach No. =  0.00
Etar = 1.0000       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.21242E+00    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.87802            PR =   1.126            ETA = 0.79645
PCN =   0.9630         CN = 0.96302            COMWK =  0.67552E+05
***** COMPRESSOR  2 PARAMETERS *****
```

```
PRSF =  0.14706E+01    ETASF =  0.95181E+00    WASF =  0.28962E-01
Z = 0.87516            PR =   2.451            ETA = 0.79689
PCN =   0.9630         CN = 0.96379            COMWK =  0.59599E+06
***** COMPRESSOR  3 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13595E-01
Z = 0.84337            PR =   4.288            ETA = 0.79607
PCN =   0.9630         CN = 0.96812            COMWK =  0.14329E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.5933            WFB =   0.1139
***** TURBINE  1 PARAMETERS *****
CNSF =  0.78196E+02    ETASF =  0.10332E+01    TFSF =  0.22625E+02
DHSF =  0.16249E+05
TF =  413.310          ETA = 0.87809           CN =  2.018
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.73490E-02    ETASF =  0.10609E+01    TFSF =  0.37873E+01
DHSF =  0.42293E+05
TF =  215.081          ETA = 0.87264           CN =  2.235
AUXWK =  0.13633E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.13633E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0557         Exit Velocity =  236.78  Gross Thrust =   1267.80
Nozzle Coeff. =  0.97307E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000     5.389   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000     5.389    ******   1.00000  ******  288.15  ******  ******
   3  0.00000     5.387    ******   1.12601  ******  300.64  ******  ******
   4  0.00000     5.389    ******   2.76007  ******  410.35  ******  ******
   5  0.00000     5.389    ******  11.83568  ******  666.53  ******  ******
   6  0.00000     4.952    ******  11.83568  ******  666.53  ******  ******
   7  0.02301     5.066    ******  11.24239  ****** 1450.00  ******  ******
   8  0.02115     5.502    ******  11.24239  ****** 1393.02  ******  ******
   9  0.02115     5.502    ******   3.21554  ****** 1081.57  ******  ******
  10  0.02115     5.502    ******   3.18339  ****** 1081.57  ******  ******
  11  0.02115     5.502    ******   1.13308  ******  871.01  ******  ******
  12  0.02115     5.502    ******   1.12175  ******  871.01  ******  ******
  13  0.02115     5.502   1.00000   1.12175  846.66  871.01   236.8  0.0557
  14  0.00000     0.436    ******  11.83568  ******  666.53  ******  ******

  Shaft Power =   1363337.63
   Net Thrust =  1267.80
 Equiv. Power =   1445081.63
    Fuel Flow =   0.1139
       S.F.C. =  83.5768
     E.S.F.C. =  78.8491
Sp. Sh. Power =   252980.78
Sp. Eq. Power =   268149.19
Sh. Th. Effy. =   0.2775
        Time Now 20:54:30
************************************************
-1
7 6 1500.0
-1
                              Time Now 20:54:30
************************************************
BERR( 1) =   -0.33821E-03
BERR( 2) =    0.22919E-03
BERR( 3) =   -0.17799E-01
BERR( 4) =    0.31362E-01
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 BERR( 5) =    0.22208E-01
 BERR( 6) =    0.27996E-01
 BERR( 7) =    0.10432E+00
 Loop   1
 BERR( 1) =   -0.31242E-03
 BERR( 2) =    0.25236E-03
 BERR( 3) =   -0.61998E-02
 BERR( 4) =    0.10152E-01
 BERR( 5) =    0.62167E-02
 BERR( 6) =    0.12790E-01
 BERR( 7) =    0.37429E-01
 Loop   2
 BERR( 1) =   -0.20372E-03
 BERR( 2) =    0.80542E-04
 BERR( 3) =   -0.19694E-05
 BERR( 4) =   -0.96291E-03
 BERR( 5) =   -0.21908E-02
 BERR( 6) =    0.52905E-02
 BERR( 7) =    0.24908E-02
 Loop   3
 BERR( 1) =    0.17178E-04
 BERR( 2) =    0.97585E-04
 BERR( 3) =   -0.13472E-03
 BERR( 4) =    0.11037E-02
 BERR( 5) =    0.13989E-02
 BERR( 6) =   -0.82724E-03
 BERR( 7) =    0.15026E-02
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 1.0000       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.21242E+00     ETASF =  0.91980E+00     WASF =  0.19204E-01
 Z = 0.85098            PR =   1.130            ETA = 0.79016
 PCN =   0.9990         CN = 0.99898            COMWK =  0.74049E+05
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.14706E+01     ETASF =  0.95181E+00     WASF =  0.28962E-01
 Z = 0.85091            PR =   2.499            ETA = 0.79019
 PCN =   0.9990         CN = 0.99900            COMWK =  0.65155E+06
 ***** COMPRESSOR  3 PARAMETERS *****
 PRSF =  0.34314E+01     ETASF =  0.95181E+00     WASF =  0.13595E-01
 Z = 0.85000            PR =   4.495            ETA = 0.79017
 PCN =   0.9990         CN = 0.99909            COMWK =  0.16012E+07
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000          DLP = 0.6344            WFB =   0.1264
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.78196E+02     ETASF =  0.10332E+01     TFSF =  0.22625E+02
 DHSF =  0.16249E+05
 TF =  414.352          ETA = 0.87988            CN =  2.058
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.73490E-02     ETASF =  0.10609E+01     TFSF =  0.37873E+01
 DHSF =  0.42293E+05
 TF =  219.659          ETA = 0.89013            CN =  2.200
 AUXWK =  0.15675E+07
 Additional Free Turbine Parameters:-
 Speed = 100.0%         Power =  0.15675E+07
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  0.0557        Exit Velocity =  254.52  Gross Thrust =   1441.36
 Nozzle Coeff. =  0.97334E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	5.691	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	5.691	******	1.00000	******	288.15	******	******
3	0.00000	5.691	******	1.12993	******	301.12	******	******
4	0.00000	5.692	******	2.82380	******	414.62	******	******
5	0.00000	5.692	******	12.69208	******	685.00	******	******
6	0.00000	5.231	******	12.69208	******	685.00	******	******
7	0.02416	5.357	******	12.05769	******	1500.00	******	******
8	0.02220	5.818	******	12.05769	******	1440.89	******	******
9	0.02220	5.818	******	3.39013	******	1116.24	******	******
10	0.02220	5.818	******	3.35623	******	1116.24	******	******
11	0.02220	5.818	******	1.15006	******	888.68	******	******
12	0.02220	5.818	******	1.13856	******	888.68	******	******
13	0.02220	5.818	1.00000	1.13856	860.70	888.68	254.5	0.0557
14	0.00000	0.461	******	12.69208	******	685.00	******	******

Shaft Power = 1567528.13
Net Thrust = 1441.36
Equiv. Power = 1660462.63
Fuel Flow = 0.1264
S.F.C. = 80.6211
E.S.F.C. = 76.1088
Sp. Sh. Power = 275433.63
Sp. Eq. Power = 291763.31
Sh. Th. Effy. = 0.2876
Time Now 20:54:30
****
-1
7 6 1550.0
-1
Time Now 20:54:30
****
BERR(1) = 0.17178E-04
BERR(2) = 0.97585E-04
BERR(3) = -0.17447E-01
BERR(4) = 0.32300E-01
BERR(5) = 0.25012E-01
BERR(6) = 0.54784E-01
BERR(7) = 0.10266E+00
Loop 1
BERR(1) = 0.39775E-03
BERR(2) = -0.17102E-02
BERR(3) = -0.55985E-03
BERR(4) = -0.12843E-01
BERR(5) = -0.19319E-01
BERR(6) = 0.16077E-01
BERR(7) = 0.37258E-02
Loop 2
BERR(1) = -0.27536E-03
BERR(2) = 0.75663E-03
BERR(3) = -0.18412E-02
BERR(4) = 0.12720E-01
BERR(5) = 0.16254E-01
BERR(6) = 0.33487E-04
BERR(7) = 0.13713E-01
Loop 3
Loop 4
BERR(1) = -0.27270E-05
BERR(2) = 0.49967E-04
BERR(3) = -0.26120E-04
BERR(4) = 0.24222E-03
BERR(5) = 0.11909E-03
BERR(6) = -0.17161E-04

```
BERR( 7) =   -0.10274E-03
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   4 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 1.0000       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.21242E+00    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.83991            PR =   1.133           ETA = 0.77974
PCN =   1.0167         CN = 1.01670           COMWK =  0.79200E+05
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.14706E+01    ETASF =  0.95181E+00    WASF =  0.28962E-01
Z = 0.84287            PR =   2.539           ETA = 0.78008
PCN =   1.0167         CN = 1.01591           COMWK =  0.69505E+06
***** COMPRESSOR  3 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13595E-01
Z = 0.85848            PR =   4.623           ETA = 0.78247
PCN =   1.0167         CN = 1.01152           COMWK =  0.17234E+07
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.6585           WFB =   0.1371
***** TURBINE  1 PARAMETERS *****
CNSF =  0.78196E+02    ETASF =  0.10332E+01    TFSF =  0.22625E+02
DHSF =  0.16249E+05
TF =  414.799          ETA = 0.87983          CN =  2.061
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.73490E-02    ETASF =  0.10609E+01    TFSF =  0.37873E+01
DHSF =  0.42293E+05
TF =  221.407          ETA = 0.89725          CN =  2.164
AUXWK =  0.17272E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.17272E+07
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.0557         Exit Velocity =  269.01  Gross Thrust =   1573.08
Nozzle Coeff. =  0.97352E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    5.869   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    5.869    ******   1.00000  ******  288.15  ******  ******
   3  0.00000    5.869    ******   1.13311  ******  301.60  ******  ******
   4  0.00000    5.870    ******   2.87660  ******  418.97  ******  ******
   5  0.00000    5.870    ******  13.29895  ******  700.57  ******  ******
   6  0.00000    5.394    ******  13.29895  ******  700.57  ******  ******
   7  0.02541    5.531    ******  12.64045  ****** 1550.00  ******  ******
   8  0.02335    6.007    ******  12.64045  ****** 1488.60  ******  ******
   9  0.02335    6.007    ******   3.52515  ****** 1153.40  ******  ******
  10  0.02335    6.007    ******   3.48990  ****** 1153.40  ******  ******
  11  0.02335    6.007    ******   1.16139  ******  912.21  ******  ******
  12  0.02335    6.007    ******   1.14978  ******  912.21  ******  ******
  13  0.02335    6.007   1.00000   1.14978  881.16  912.21   269.0  0.0557
  14  0.00000    0.475    ******  13.29895  ******  700.57  ******  ******

  Shaft Power =   1727170.63
   Net Thrust =  1573.08
 Equiv. Power =   1828598.00
    Fuel Flow =   0.1371
       S.F.C. =  79.3502
     E.S.F.C. =  74.9489
Sp. Sh. Power =    294271.19
Sp. Eq. Power =    311552.13
Sh. Th. Effy. =   0.2922
```

```
       Time Now 20:54:30
************************************************
-1
7 6 1600.0
-1
                                Time Now 20:54:30
************************************************
BERR( 1) =  -0.27270E-05
BERR( 2) =   0.49967E-04
BERR( 3) =  -0.16869E-01
BERR( 4) =   0.30505E-01
BERR( 5) =   0.23246E-01
BERR( 6) =   0.48638E-01
BERR( 7) =   0.97044E-01
Loop   1
BERR( 1) =   0.53996E-04
BERR( 2) =   0.20456E-03
BERR( 3) =  -0.75482E-04
BERR( 4) =   0.85229E-03
BERR( 5) =  -0.61280E-03
BERR( 6) =   0.23278E-01
BERR( 7) =   0.22402E-02
Loop   2
BERR( 1) =  -0.12819E-04
BERR( 2) =  -0.57977E-04
BERR( 3) =   0.27722E-04
BERR( 4) =  -0.11932E-03
BERR( 5) =   0.80950E-04
BERR( 6) =  -0.17870E-01
BERR( 7) =   0.95950E-03
Loop   3
Loop   4
BERR( 1) =   0.12182E-05
BERR( 2) =   0.48010E-05
BERR( 3) =  -0.43791E-05
BERR( 4) =   0.13664E-04
BERR( 5) =  -0.10568E-04
BERR( 6) =   0.16809E-01
BERR( 7) =  -0.13175E-02
Loop   5
BERR( 1) =   0.71774E-06
BERR( 2) =  -0.14355E-06
BERR( 3) =  -0.31491E-06
BERR( 4) =  -0.77882E-06
BERR( 5) =  -0.18917E-05
BERR( 6) =   0.35457E-04
BERR( 7) =   0.52572E-05
1
   ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   5 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =     0.0     I.S.A. Dev. =   0.000      Mach No. =  0.00
Etar = 1.0000      Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.21242E+00    ETASF =  0.91980E+00    WASF =  0.19204E-01
Z = 0.82990           PR =   1.136           ETA = 0.77077
PCN =   1.0324         CN = 1.03236            COMWK =  0.83878E+05
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.14706E+01    ETASF =  0.95181E+00    WASF =  0.28962E-01
Z = 0.83590           PR =   2.574           ETA = 0.77120
PCN =   1.0324         CN = 1.03083            COMWK =  0.73505E+06
***** COMPRESSOR  3 PARAMETERS *****
PRSF =  0.34314E+01    ETASF =  0.95181E+00    WASF =  0.13595E-01
Z = 0.86755           PR =   4.745           ETA = 0.77500
PCN =   1.0324         CN = 1.02234            COMWK =  0.18407E+07
```

***** COMBUSTION CHAMBER PARAMETERS *****
ETASF = 0.99000E+00
ETA = 0.99000 DLP = 0.6796 WFB = 0.1479
***** TURBINE 1 PARAMETERS *****
CNSF = 0.78196E+02 ETASF = 0.10332E+01 TFSF = 0.22625E+02
DHSF = 0.16249E+05
TF = 415.099 ETA = 0.87964 CN = 2.060
AUXWK = 0.00000E+00
***** TURBINE 2 PARAMETERS *****
CNSF = 0.73490E-02 ETASF = 0.10609E+01 TFSF = 0.37873E+01
DHSF = 0.42293E+05
TF = 222.631 ETA = 0.90088 CN = 2.129
AUXWK = 0.18821E+07
Additional Free Turbine Parameters:-
Speed = 100.0% Power = 0.18821E+07
***** CONVERGENT NOZZLE 1 PARAMETERS *****
NCOSF = 0.10000E+01
Area = 0.0557 Exit Velocity = 283.50 Gross Thrust = 1704.57
Nozzle Coeff. = 0.97372E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers = 1.0000

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	6.027	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	6.027	******	1.00000	******	288.15	******	******
3	0.00000	6.027	******	1.13582	******	302.02	******	******
4	0.00000	6.027	******	2.92321	******	422.87	******	******
5	0.00000	6.027	******	13.87111	******	715.21	******	******
6	0.00000	5.539	******	13.87111	******	715.21	******	******
7	0.02670	5.687	******	13.19156	******	1600.00	******	******
8	0.02454	6.175	******	13.19156	******	1536.26	******	******
9	0.02454	6.175	******	3.66242	******	1191.44	******	******
10	0.02454	6.175	******	3.62580	******	1191.44	******	******
11	0.02454	6.175	******	1.17477	******	937.56	******	******
12	0.02454	6.175	******	1.16302	******	937.56	******	******
13	0.02454	6.175	1.00000	1.16302	903.33	937.56	283.5	0.0557
14	0.00000	0.488	******	13.87111	******	715.21	******	******

Shaft Power = 1882108.13
Net Thrust = 1704.57
Equiv. Power = 1992013.38
Fuel Flow = 0.1479
S.F.C. = 78.5693
E.S.F.C. = 74.2344
Sp. Sh. Power = 312282.59
Sp. Eq. Power = 330518.25
Sh. Th. Effy. = 0.2951
Time Now 20:54:30
****
-3

Appendix B Aeroderivative IGT engines simulation files

B.1 Input and result file for ICR SS-ADIGT engine performance simulation

TURBOMATCH SCHEME - Windows NT version (October 1999)
LIMITS:100 Codewords, 800 Brick Data Items, 50 Station Vector
15 BD Items printable by any call of:-

```
OUTPUT, OUTPBD, OUTPSV, PLOTIT, PLOTBD or PLOTSV
 Input "Program" follows
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!PERFORMANCE SIMULATION OF AN INTERCOOLED/RECUPERATED TWO-SPOOL TURBOSHAFT!
!HELI-DERIVATIVE INDUSTRIAL ENGINE WITH A FREE POWER TURBINE            !
!INSPIRED BY TURBOMECCA MAKILA 2A ENGINE CORE                           !
!MODELLED BY BARINYIMA NKOI, JULY 2012                                  !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

OD SI KE CT FP
 -1
 -1
INTAKE S1-2         D1-4          R100
COMPRE S2-3         D5-10         R101   V5    V6
ARITHY              D70-74
DUCTER S3-4         D11-14
COMPRE S4-5         D15,6,17-20   R104   V15
PREMAS S5,6,18      D21-24
HETCOL S6-7         D25-28
ARITHY              D75-81
BURNER S7-8         D29-31        R107
MIXEES S8,18,9
TURBIN S9-10        D32-39,115           V33
DUCTER S10-11       D41-44        R108
TURBIN S11-12       D45-53               V45   V46
HETHOT S6,12,16     D54-57
DUCTER S12-13       D58-61        R110
NOZCON S13-14,1     D62           R111
PERFOR S1,0,0       D45,64-66,111,100,107,0,0,0,0,0,0
CODEND

!INTAKE
 1  0.0       !ALTITUDE:INLET
 2  0.0       !ISA DEVIATION
 3  0.0       !MACH NO
 4  0.9951    !PRESSURE RECOVERY
!COMPRE AXIAL
 5  0.80      !SURGE MARGIN
 6  0.8       !ROTATIONAL SPEED
 7  2.5       !PRESSURE RATIO
 8  0.78      !COMPRE EFFICIENCY
 9  0.0       !ERROR SWITCH
 10  2.0      !COMPRE MAP
!DUCTER INTERCOOLER
 11  2.0      !INTERCOOLER
 12  0.04     !PRESSURE LOSS
 13  0.40     !EFFECTIVENESS
 14  100000.0   !LIMITING VALUE OF FUEL FLOW
!COMPRE CENTRIFUGAL
 15  0.80     !SURGE MARGIN
 16  0.8      !ROTATIONAL SPEED
 17  4.5      !PRESSURE RATIO
 18  0.78     !COMPRE EFFICIENCY
 19  1.0      !ERROR SWITCH
 20  4.0      !COMPRE MAP
!PREMAS
 21  0.80     !LAMBDA(W) {W5/W4}
 22  0.0      !DELTA(W)
 23  1.0      !LAMBDA(P)
 24  0.0      !DELTA(P)
!HETCOL
 25  0.03     !COLD SIDE PRESSURE LOSS
 26  0.55     !EFFECTIVENESS
 27  1.0      !TYPE:RECUPERATOR
```

```
 28  0.02       !MASS FLOW LEAKAGE
!BURNER
 29  0.05       !PRESSURE LOSS
 30  0.99       !COMBUS EFFICIENCY
 31  -1.0       !FUEL FLOW CALCULATED
!COMPRE TURBINE
 32  0.0        !COMPRE TURBINE
 33  -1.0       !REL NON-D MASS FLOW
 34  -1.0       !REL NON-D SPEED
 35  0.87       !TURBINE EFFICIENCY
 36  -1.0       !REL ROT SPEED=COMPRE ROT SPEED
 37  2.0        !COMP NO
 38  1.0        !TURBINE MAP
 39  -1.0       !POWER LAW
 !AS IN 115     !COMWRK
!DUCTER
 41  0.0        !DUCTER
 42  0.01       !PRESSURE LOSS
 43  0.0
 44  100000.0
!POWER TURBINE
 45  1567000.0  !POWER TURBINE OUTPUT
 46  -1.0       !REL NON-D MASS FLOW
 47  -1.0       !REL NON-D SPEED
 48  0.88       !TURBINE EFFICIENCY
 49  1.0        !REL ROT SPEED
 50  0.0        !COMP NO
 51  5.0        !TURBINE MAP
 52  1000.0     !POWER LAW INDEX
 53  -1.0       !SET FOR POWER TURBINE
!HETHOT
 54  0.03       !HOT SIDE PRESSURE LOSS
 55  0.55       !EFFECTIVENESS
 56  1.0        !TYPE:RECUPERATOR
 57  0.02       !MASS FLOW LEAKAGE
!DUCTER
 58  0.0        !DUCTER
 59  0.01       !PRESSURE LOSS
 60  0.0
 61  100000.0
!NOZCON
 62  -1.0       !SWITCH TO FIXED AREA

 !PERFOR
 !AS IN 48      !POWER TURBINE:POWER OUTPUT
 64  1.0        !PROPELLER EFFICIENCY:PERFORMANCE
 65  0.0        !SCALING INDEX
 66  0.0        !SHAFT POWER
!ARITHY: COMPREAXIALPCN=COMPRECENTRIFUGALPCN
 70  5.0        !COPY
 71  -1.0
 72  16.0       !COMPRECENTRIFUGALPCN
 73  -1.0
 74  6.0        !COMPREAXIALPCN
!ARITHY: COMPRETURBINEWORK=COMPREAXIALWORK+COMPRECENTRIFUGALWORK
 75  1.0        !ADD
 76  -1.0
 77  115.0      !COMPRETURBINEWORK
 78  -1.0
 79  101.0      !COMPREAXIALWORK
 80  -1.0
 81  104.0      !COMPRECENTRIFUGALWORK
 -1
 1 2 5.53       !MASS FLOW
```

```
4 6 300.0      !INTERCOOLER OUTLET TEMPERATURE
8 6 1500.0     !TET
-1
                                   Time Now 12:21:49
************************************************
            The Units for this Run are as follows:-
Temperature = K   Pressure = Atmospheres   Length = metres
Area = sq metres  Mass Flow = kg/sec       Velocity = metres/sec
Force = Newtons   s.f.c.(Thrust) =  mg/N sec   s.f.c.(Power) = mug/J
Sp. Thrust =    N/kg/sec     Power =   Watts

    ***** DESIGN POINT ENGINE CALCULATIONS *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 0.9951       Momentum Drag =       0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.37651E+01    ETASF =  0.87288E+00    WASF =  0.24254E-01
Z = 0.80000            PR =   2.500            ETA = 0.78000
PCN =   0.8000         CN = 0.80000            COMWK =  0.61411E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000          DLP = 0.0995            WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1384.51      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.52711E+01    ETASF =  0.89655E+00    WASF =  0.17100E-01
Z = 0.80000            PR =   4.500            ETA = 0.78000
PCN =   0.8000         CN = 0.80000            COMWK =  0.11461E+07
HETYP =  1.0 HEUA =       2.526
HETYP =  1.0 HEUA =       2.587
HETYP =  1.0 HEUA =       2.586
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETAD =  0.55000E+00
ETA = 0.55000          DLP = 0.3224
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.5212            WFB =   0.1073
***** TURBINE  1 PARAMETERS *****
CNSF =  0.12726E+03    ETASF =  0.10132E+01    TFSF =  0.19345E+02
DHSF =  0.66310E+04
TF =  401.640          ETA = 0.87000           CN =  2.800
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.71786E-02    ETASF =  0.10490E+01    TFSF =  0.40186E+01
DHSF =  0.45558E+05
TF =  219.627          ETA = 0.88000           CN =  2.200
AUXWK =  0.15670E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.15670E+07
HETYP =  1.0 HEUA =       2.586
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETAD =  0.55000E+00 HEUA =       2.586 ETASF =  0.00000E+00
ETA =  0.5500          DLP = 0.0307    TOTHOT =   696.2859
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.1629         Exit Velocity =   80.72  Gross Thrust =    441.96
Nozzle Coeff. =  0.97122E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal    Vel   Area
   1  0.00000     5.530   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000     5.530    ******   0.99510  ******  288.15  ******  ******
   3  0.00000     5.530    ******   2.48775  ******  398.40  ******  ******
   4  0.00000     5.530    ******   2.38824  ******  300.00  ******  ******
   5  0.00000     5.530    ******  10.74709  ******  504.29  ******  ******
   6  0.00000     4.424    ******  10.74709  ******  504.29  ******  ******
```

```
   7  0.00000    4.424   ******  10.42467  ******  681.40  ******  ******
   8  0.02426    4.531   ******   9.90344  ****** 1500.00  ******  ******
   9  0.01941    5.637   ******   9.90344  ****** 1322.15  ******  ******
  10   0.01941    5.637   ******   3.39651  ****** 1064.71  ******  ******
  11   0.01941    5.637   ******   3.36255  ****** 1064.71  ******  ******
  12   0.01941    5.637   ******   1.02244  ******  826.42  ******  ******
  13   0.01941    5.637   ******   1.01222  ******  826.42  ******  ******
  14   0.01941    5.637  1.00000   1.01222  823.55  826.42    80.7  0.1629
  15   0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
  16   0.01941    5.637   ******   0.99177  ******  696.29  ******  ******
  17   0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
  18   0.00000    1.106   ******  10.74709  ******  504.29  ******  ******
 Shaft Power =   1567000.00
  Net Thrust =   441.96
 Equiv. Power =   1595496.50
   Fuel Flow =   0.1073
      S.F.C. =  68.4894
    E.S.F.C. =  67.2661
Sp. Sh. Power =    283363.47
Sp. Eq. Power =    288516.53
Sh. Th. Effy. =  0.3386
        Time Now 12:21:49
************************************************
-1
8 6 1350.0      !OD CALCULATION: TET = 1350.0K
-1
                                     Time Now 12:21:49
************************************************
BERR( 1) =    0.78224E-07
BERR( 2) =    0.62672E-01
BERR( 3) =   -0.69596E-01
BERR( 4) =   -0.83456E-01
BERR( 5) =   -0.67518E-01
BERR( 6) =   -0.30794E+00
Loop   1
BERR( 1) =   -0.30889E-03
BERR( 2) =    0.47983E-01
BERR( 3) =   -0.53617E-01
BERR( 4) =   -0.64169E-01
BERR( 5) =   -0.42164E-01
BERR( 6) =   -0.23532E+00
Loop   2
BERR( 1) =   -0.12129E-02
BERR( 2) =    0.34994E-01
BERR( 3) =   -0.39900E-01
BERR( 4) =   -0.47472E-01
BERR( 5) =   -0.12446E-01
BERR( 6) =   -0.16307E+00
Loop   3
BERR( 1) =   -0.13862E-02
BERR( 2) =    0.23759E-01
BERR( 3) =   -0.29113E-01
BERR( 4) =   -0.33590E-01
BERR( 5) =    0.16173E-01
BERR( 6) =   -0.95457E-01
Loop   4
BERR( 1) =   -0.16489E-03
BERR( 2) =    0.13704E-01
BERR( 3) =   -0.20427E-01
BERR( 4) =   -0.21509E-01
BERR( 5) =    0.36901E-01
BERR( 6) =   -0.37151E-01
Loop   5
BERR( 1) =    0.15398E-02
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 BERR( 2) =   0.41946E-02
 BERR( 3) =  -0.12018E-01
 BERR( 4) =  -0.91483E-02
 BERR( 5) =   0.34318E-01
 BERR( 6) =   0.26949E-02
 Loop   6
 BERR( 1) =   0.11632E-03
 BERR( 2) =   0.96570E-03
 BERR( 3) =  -0.65075E-02
 BERR( 4) =  -0.26665E-02
 BERR( 5) =   0.44782E-02
 BERR( 6) =  -0.41325E-02
 Loop   7
 BERR( 1) =  -0.30015E-03
 BERR( 2) =   0.17713E-04
 BERR( 3) =  -0.36883E-02
 BERR( 4) =  -0.11858E-02
 BERR( 5) =   0.33939E-02
 BERR( 6) =   0.30703E-04
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   7 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0      I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 0.9951       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.37651E+01    ETASF =  0.87288E+00    WASF =  0.24254E-01
 Z = 0.89342            PR =   2.337            ETA = 0.76427
 PCN =   0.6969         CN = 0.69694            COMWK =  0.46070E+06
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.4000          DLP = 0.0930            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED: 1030.15      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.52711E+01    ETASF =  0.89655E+00    WASF =  0.17100E-01
 Z = 0.75347            PR =   3.631            ETA = 0.77395
 PCN =   0.6969         CN = 0.69694            COMWK =  0.76811E+06
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.60500          DLP = 0.2564
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000          DLP = 0.4328            WFB =   0.0703
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.12726E+03    ETASF =  0.10132E+01    TFSF =  0.19345E+02
 DHSF =  0.66310E+04
 TF =  405.123          ETA = 0.90046           CN =  2.570
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.71786E-02    ETASF =  0.10490E+01    TFSF =  0.40186E+01
 DHSF =  0.45558E+05
 TF =  206.820          ETA = 0.81942           CN =  2.316
 AUXWK =  0.88373E+06
 Additional Free Turbine Parameters:-
 Speed = 100.0%         Power =  0.88373E+06
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
 ETA =  0.6050          DLP = 0.0187     TOTHOT =   659.7021
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  0.1629         Exit Velocity =   61.65  Gross Thrust =    269.46
 Nozzle Coeff. =  0.97115E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
    1  0.00000     4.432   1.00000   1.00000  288.15  288.15     0.0  ******
    2  0.00000     4.432    ******   0.99510  ******  288.15  ******  ******
```

```
   3  0.00000    4.432   ******  2.32564  ******  391.39  ******  ******
   4  0.00000    4.430   ******  2.23261  ******  300.00  ******  ******
   5  0.00000    4.430   ******  8.10699  ******  471.30  ******  ******
   6  0.00000    3.544   ******  8.10699  ******  471.30  ******  ******
   7  0.00000    3.544   ******  7.85061  ******  663.78  ******  ******
   8  0.01983    3.615   ******  7.41786  ****** 1350.00  ******  ******
   9  0.01587    4.501   ******  7.41786  ****** 1191.29  ******  ******
  10  0.01587    4.501   ******  2.73502  ******  960.95  ******  ******
  11  0.01587    4.501   ******  2.70767  ******  960.95  ******  ******
  12  0.01587    4.501   ******  1.01877  ******  789.54  ******  ******
  13  0.01587    4.501   ******  1.00859  ******  789.54  ******  ******
  14  0.01587    4.501  1.00000  1.00859  787.82  789.54    61.6  0.1629
  15  0.00000    0.000   ******  0.00000  ******    0.00  ******  ******
  16  0.01587    4.501   ******  1.00003  ******  659.70  ******  ******
  17  0.00000    0.000   ******  0.00000  ******    0.00  ******  ******
  18  0.00000    0.886   ******  8.10699  ******  471.30  ******  ******
  Shaft Power =   883727.63
   Net Thrust =   269.46
 Equiv. Power =   901101.69
    Fuel Flow =   0.0703
       S.F.C. =  79.5489
     E.S.F.C. =  78.0151
Sp. Sh. Power =   199411.27
Sp. Eq. Power =   203331.69
Sh. Th. Effy. =  0.2915
        Time Now 12:21:49
************************************************
-1
8 6 1400.0      !OD CALCULATION: TET = 1400.0K
-1
                                  Time Now 12:21:49
************************************************
BERR( 1) =  -0.30015E-03
BERR( 2) =  -0.20009E-01
BERR( 3) =   0.16498E-01
BERR( 4) =   0.18658E-01
BERR( 5) =   0.72875E-01
BERR( 6) =   0.11014E+00
Loop   1
BERR( 1) =  -0.18873E-02
BERR( 2) =  -0.13404E-01
BERR( 3) =   0.85492E-02
BERR( 4) =   0.94783E-02
BERR( 5) =   0.45863E-01
BERR( 6) =   0.61455E-01
Loop   2
BERR( 1) =  -0.32786E-02
BERR( 2) =  -0.47920E-02
BERR( 3) =  -0.11536E-02
BERR( 4) =  -0.10652E-03
BERR( 5) =   0.20718E-01
BERR( 6) =   0.12606E-01
Loop   3
BERR( 1) =  -0.45564E-03
BERR( 2) =  -0.88047E-04
BERR( 3) =   0.67185E-03
BERR( 4) =  -0.40168E-03
BERR( 5) =   0.48736E-02
BERR( 6) =   0.87466E-03
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =   0.000       Mach No. =  0.00
Etar = 0.9951       Momentum Drag =       0.00
```

```
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.37651E+01    ETASF =  0.87288E+00    WASF =  0.24254E-01
Z = 0.86615            PR =   2.398            ETA = 0.77826
PCN =   0.7286         CN = 0.72858            COMWK =  0.50524E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000          DLP = 0.0954            WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1131.98     KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.52711E+01    ETASF =  0.89655E+00    WASF =  0.17100E-01
Z = 0.77008            PR =   3.899            ETA = 0.77821
PCN =   0.7286         CN = 0.72858            COMWK =  0.87989E+06
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.59181          DLP = 0.2773
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.4627            WFB =   0.0813
***** TURBINE  1 PARAMETERS *****
CNSF =  0.12726E+03    ETASF =  0.10132E+01    TFSF =  0.19345E+02
DHSF =  0.66310E+04
TF =  403.704          ETA = 0.89053           CN =  2.639
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.71786E-02    ETASF =  0.10490E+01    TFSF =  0.40186E+01
DHSF =  0.45558E+05
TF =  210.169          ETA = 0.84297           CN =  2.274
AUXWK =  0.10910E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.10910E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.5918          DLP = 0.0222    TOTHOT =   671.6780
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.1629         Exit Velocity =   67.66  Gross Thrust =    319.71
Nozzle Coeff. =  0.97120E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	4.786	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	4.786	******	0.99510	******	288.15	******	******
3	0.00000	4.786	******	2.38591	******	392.98	******	******
4	0.00000	4.784	******	2.29047	******	300.00	******	******
5	0.00000	4.784	******	8.93161	******	481.59	******	******
6	0.00000	3.827	******	8.93161	******	481.59	******	******
7	0.00000	3.827	******	8.65435	******	671.03	******	******
8	0.02125	3.909	******	8.19162	******	1400.00	******	******
9	0.01700	4.865	******	8.19162	******	1234.74	******	******
10	0.01700	4.865	******	2.96508	******	996.45	******	******
11	0.01700	4.865	******	2.93543	******	996.45	******	******
12	0.01700	4.865	******	1.02126	******	801.88	******	******
13	0.01700	4.865	******	1.01105	******	801.88	******	******
14	0.01700	4.865	1.00000	1.01105	799.82	801.88	67.7	0.1629
15	0.00000	0.000	******	0.00000	******	0.00	******	******
16	0.01700	4.865	******	0.99907	******	671.68	******	******
17	0.00000	0.000	******	0.00000	******	0.00	******	******
18	0.00000	0.957	******	8.93161	******	481.59	******	******

```
 Shaft Power =   1091018.25
  Net Thrust =   319.71
 Equiv. Power =   1111632.00
   Fuel Flow =   0.0813
      S.F.C. =  74.5457
    E.S.F.C. =  73.1633
Sp. Sh. Power =    227953.17
Sp. Eq. Power =    232260.11
```

```
Sh. Th. Effy. =   0.3111
        Time Now 12:21:49
***********************************************
-1
8 6 1450.0
-1
                                        Time Now 12:21:49
***********************************************
BERR( 1) =   -0.45564E-03
BERR( 2) =   -0.19435E-01
BERR( 3) =    0.21820E-01
BERR( 4) =    0.19940E-01
BERR( 5) =    0.38387E-01
BERR( 6) =    0.10479E+00
Loop   1
BERR( 1) =    0.85118E-03
BERR( 2) =   -0.10580E-01
BERR( 3) =    0.10359E-01
BERR( 4) =    0.10455E-01
BERR( 5) =    0.26729E-01
BERR( 6) =    0.58387E-01
Loop   2
BERR( 1) =    0.22752E-02
BERR( 2) =    0.21416E-03
BERR( 3) =   -0.46305E-02
BERR( 4) =   -0.16169E-02
BERR( 5) =    0.14411E-01
BERR( 6) =    0.57002E-02
Loop   3
BERR( 1) =   -0.18398E-03
BERR( 2) =   -0.21375E-03
BERR( 3) =    0.22028E-02
BERR( 4) =    0.53154E-03
BERR( 5) =   -0.69416E-03
BERR( 6) =    0.11174E-02
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 0.9951       Momentum Drag =       0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.37651E+01     ETASF =  0.87288E+00     WASF =  0.24254E-01
Z = 0.83748             PR =   2.451            ETA = 0.78492
PCN =   0.7609          CN = 0.76094            COMWK =  0.55253E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000           DLP = 0.0975            WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1240.94      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.52711E+01     ETASF =  0.89655E+00     WASF =  0.17100E-01
Z = 0.78473             PR =   4.171            ETA = 0.78000
PCN =   0.7609          CN = 0.76094            COMWK =  0.99865E+06
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.57159           DLP = 0.2982
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000           DLP = 0.4912            WFB =   0.0933
***** TURBINE  1 PARAMETERS *****
CNSF =  0.12726E+03     ETASF =  0.10132E+01     TFSF =  0.19345E+02
DHSF =  0.66310E+04
TF =  402.602           ETA = 0.88120           CN =  2.709
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.71786E-02     ETASF =  0.10490E+01     TFSF =  0.40186E+01
```

```
DHSF =  0.45558E+05
TF =  213.949          ETA = 0.85911          CN =  2.235
AUXWK =  0.13086E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.13086E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.5716          DLP = 0.0260     TOTHOT =   684.6348
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.1629         Exit Velocity =   73.91  Gross Thrust =    375.14
Nozzle Coeff. =  0.97123E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
    1  0.00000    5.134   1.00000   1.00000  288.15  288.15     0.0  ******
    2  0.00000    5.134   ******  0.99510  ******  288.15  ******  ******
    3  0.00000    5.134   ******  2.43855  ******  395.02  ******  ******
    4  0.00000    5.133   ******  2.34101  ******  300.00  ******  ******
    5  0.00000    5.133   ******  9.76545  ******  491.96  ******  ******
    6  0.00000    4.106   ******  9.76545  ******  491.96  ******  ******
    7  0.00000    4.106   ******  9.46726  ******  676.96  ******  ******
    8  0.02272    4.199   ******  8.97604  ****** 1450.00  ******  ******
    9  0.01818    5.226   ******  8.97604  ****** 1278.26  ******  ******
   10  0.01818    5.226   ******  3.18651  ****** 1031.73  ******  ******
   11  0.01818    5.226   ******  3.15464  ****** 1031.73  ******  ******
   12  0.01818    5.226   ******  1.02331  ******  815.83  ******  ******
   13  0.01818    5.226   ******  1.01307  ******  815.83  ******  ******
   14  0.01818    5.226  1.00000   1.01307  813.37  815.83    73.9  0.1629
   15  0.00000    0.000   ******  0.00000  ******    0.00  ******  ******
   16  0.01818    5.226   ******  0.99731  ******  684.63  ******  ******
   17  0.00000    0.000   ******  0.00000  ******    0.00  ******  ******
   18  0.00000    1.027   ******  9.76545  ******  491.96  ******  ******

  Shaft Power =   1308602.75
   Net Thrust =   375.14
 Equiv. Power =   1332790.50
    Fuel Flow =   0.0933
       S.F.C. =  71.3038
     E.S.F.C. =  70.0098
Sp. Sh. Power =    254906.00
Sp. Eq. Power =    259617.58
Sh. Th. Effy. =   0.3252
         Time Now 12:21:49
************************************************
-1
8 6 1500.0
-1
                           Time Now 12:21:49
************************************************
BERR( 1) =   -0.18398E-03
BERR( 2) =   -0.18911E-01
BERR( 3) =    0.23864E-01
BERR( 4) =    0.21438E-01
BERR( 5) =    0.19368E-01
BERR( 6) =    0.10495E+00
Loop   1
BERR( 1) =   -0.75825E-03
BERR( 2) =   -0.86930E-02
BERR( 3) =    0.10761E-01
BERR( 4) =    0.98028E-02
BERR( 5) =    0.11638E-01
BERR( 6) =    0.51302E-01
Loop   2
BERR( 1) =   -0.12439E-02
```

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BERR( 2) =   0.21119E-03
BERR( 3) =  -0.84963E-03
BERR( 4) =  -0.89192E-03
BERR( 5) =   0.61552E-02
BERR( 6) =   0.53802E-02
Loop   3
BERR( 1) =   0.94767E-04
BERR( 2) =  -0.16215E-04
BERR( 3) =   0.10080E-03
BERR( 4) =   0.34781E-04
BERR( 5) =   0.10159E-02
BERR( 6) =   0.11498E-02
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =     0.0    I.S.A. Dev. =   0.000     Mach No. =  0.00
Etar = 0.9951      Momentum Drag =     0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.37651E+01    ETASF =  0.87288E+00    WASF =  0.24254E-01
Z = 0.80016           PR =   2.498          ETA = 0.78003
PCN =   0.7992        CN = 0.79916          COMWK =  0.61261E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000         DLP = 0.0994          WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1380.96     KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.52711E+01    ETASF =  0.89655E+00    WASF =  0.17100E-01
Z = 0.79782           PR =   4.485          ETA = 0.78000
PCN =   0.7992        CN = 0.79916          COMWK =  0.11416E+07
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.55038         DLP = 0.3226
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000         DLP = 0.5225          WFB =   0.1072
***** TURBINE  1 PARAMETERS *****
CNSF =  0.12726E+03    ETASF =  0.10132E+01    TFSF =  0.19345E+02
DHSF =  0.66310E+04
TF =  401.806         ETA = 0.87060         CN =  2.797
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.71786E-02    ETASF =  0.10490E+01    TFSF =  0.40186E+01
DHSF =  0.45558E+05
TF =  219.911         ETA = 0.88102         CN =  2.200
AUXWK =  0.15628E+07
Additional Free Turbine Parameters:-
Speed = 100.0%        Power =  0.15628E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.5504         DLP = 0.0305    TOTHOT =   696.6346
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.1629        Exit Velocity =   80.70  Gross Thrust =    441.34
Nozzle Coeff. =  0.97127E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000     5.523   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000     5.523    ******   0.99510  ******  288.15  ******  ******
   3  0.00000     5.523    ******   2.48560  ******  398.28  ******  ******
   4  0.00000     5.523    ******   2.38617  ******  300.00  ******  ******
   5  0.00000     5.523    ******  10.70138  ******  503.74  ******  ******
   6  0.00000     4.419    ******  10.70138  ******  503.74  ******  ******
   7  0.00000     4.419    ******  10.37874  ******  681.69  ******  ******
   8  0.02425     4.526    ******   9.85625  ****** 1500.00  ******  ******
   9  0.01940     5.630    ******   9.85625  ****** 1322.06  ******  ******
```

```
  10   0.01940    5.630    ******   3.39204  ****** 1065.19  ******  ******
  11   0.01940    5.630    ******   3.35812  ****** 1065.19  ******  ******
  12   0.01940    5.630    ******   1.02550  ******  827.28  ******  ******
  13   0.01940    5.630    ******   1.01524  ******  827.28  ******  ******
  14   0.01940    5.630   1.00000   1.01524  824.37  827.28    80.7  0.1629
  15   0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  16   0.01940    5.630    ******   0.99496  ******  696.63  ******  ******
  17   0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  18   0.00000    1.105    ******  10.70138  ******  503.74  ******  ******

  Shaft Power =   1562751.75
   Net Thrust =   441.34
 Equiv. Power =   1591207.88
    Fuel Flow =   0.1072
       S.F.C. =  68.5686
     E.S.F.C. =  67.3423
Sp. Sh. Power =    282968.50
Sp. Eq. Power =    288121.06
Sh. Th. Effy. =   0.3382
        Time Now 12:21:49
***********************************************
-1
8 6 1550.0
-1
                                   Time Now 12:21:49
***********************************************
BERR( 1) =    0.94767E-04
BERR( 2) =   -0.18110E-01
BERR( 3) =    0.21818E-01
BERR( 4) =    0.22030E-01
BERR( 5) =    0.51363E-01
BERR( 6) =    0.10677E+00
Loop   1
BERR( 1) =    0.28884E-03
BERR( 2) =   -0.42927E-02
BERR( 3) =    0.15799E-02
BERR( 4) =    0.32164E-02
BERR( 5) =    0.21141E-01
BERR( 6) =    0.35247E-01
Loop   2
BERR( 1) =   -0.97962E-04
BERR( 2) =    0.53600E-03
BERR( 3) =   -0.13633E-02
BERR( 4) =   -0.14949E-02
BERR( 5) =    0.40059E-02
BERR( 6) =    0.22070E-02
1

     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0      I.S.A. Dev. =    0.000       Mach No. =  0.00
Etar = 0.9951       Momentum Drag =       0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.37651E+01     ETASF =  0.87288E+00     WASF =  0.24254E-01
Z = 0.77422             PR =   2.531             ETA = 0.77235
PCN =   0.8266          CN = 0.82663             COMWK =  0.66072E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000           DLP = 0.1007             WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1494.00      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.52711E+01     ETASF =  0.89655E+00     WASF =  0.17100E-01
Z = 0.80861             PR =   4.731             ETA = 0.77522
PCN =   0.8266          CN = 0.82663             COMWK =  0.12597E+07
```

***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.53599 DLP = 0.3398
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF = 0.99000E+00
ETA = 0.99000 DLP = 0.5464 WFB = 0.1192
***** TURBINE 1 PARAMETERS *****
CNSF = 0.12726E+03 ETASF = 0.10132E+01 TFSF = 0.19345E+02
DHSF = 0.66310E+04
TF = 401.422 ETA = 0.86479 CN = 2.847
AUXWK = 0.00000E+00
***** TURBINE 2 PARAMETERS *****
CNSF = 0.71786E-02 ETASF = 0.10490E+01 TFSF = 0.40186E+01
DHSF = 0.45558E+05
TF = 222.905 ETA = 0.89211 CN = 2.164
AUXWK = 0.17807E+07
Additional Free Turbine Parameters:-
Speed = 100.0% Power = 0.17807E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA = 0.5360 DLP = 0.0344 TOTHOT = 711.1658
***** CONVERGENT NOZZLE 1 PARAMETERS *****
NCOSF = 0.10000E+01
Area = 0.1629 Exit Velocity = 86.55 Gross Thrust = 497.83
Nozzle Coeff. = 0.97132E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers = 1.0000

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	5.803	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	5.803	******	0.99510	******	288.15	******	******
3	0.00000	5.803	******	2.51845	******	401.17	******	******
4	0.00000	5.802	******	2.41772	******	300.00	******	******
5	0.00000	5.802	******	11.43739	******	513.85	******	******
6	0.00000	4.642	******	11.43739	******	513.85	******	******
7	0.00000	4.642	******	11.09754	******	690.67	******	******
8	0.02568	4.761	******	10.55116	******	1550.00	******	******
9	0.02055	5.922	******	10.55116	******	1365.58	******	******
10	0.02055	5.922	******	3.57128	******	1100.09	******	******
11	0.02055	5.922	******	3.53557	******	1100.09	******	******
12	0.02055	5.922	******	1.02843	******	843.97	******	******
13	0.02055	5.922	******	1.01814	******	843.97	******	******
14	0.02055	5.922	1.00000	1.01814	840.63	843.97	86.6	0.1629
15	0.00000	0.000	******	0.00000	******	0.00	******	******
16	0.02055	5.922	******	0.99406	******	711.17	******	******
17	0.00000	0.000	******	0.00000	******	0.00	******	******
18	0.00000	1.160	******	11.43739	******	513.85	******	******

Shaft Power = 1780709.00
Net Thrust = 497.83
Equiv. Power = 1812807.25
Fuel Flow = 0.1192
S.F.C. = 66.9479
E.S.F.C. = 65.7625
Sp. Sh. Power = 306863.19
Sp. Eq. Power = 312394.59
Sh. Th. Effy. = 0.3464
Time Now 12:21:49
****
-1
8 6 1600.0
-1
Time Now 12:21:49
****
BERR(1) = -0.97962E-04
BERR(2) = -0.17019E-01
BERR(3) = 0.20042E-01

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 BERR( 4) =   0.20747E-01
 BERR( 5) =   0.67764E-01
 BERR( 6) =   0.10416E+00
 Loop   1
 BERR( 1) =  -0.34991E-03
 BERR( 2) =  -0.91160E-03
 BERR( 3) =   0.95809E-03
 BERR( 4) =   0.71710E-03
 BERR( 5) =   0.91020E-02
 BERR( 6) =   0.93874E-02
 Loop   2
 BERR( 1) =  -0.15940E-04
 BERR( 2) =  -0.59383E-05
 BERR( 3) =  -0.17845E-04
 BERR( 4) =  -0.32654E-04
 BERR( 5) =   0.11548E-02
 BERR( 6) =   0.88015E-03
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 0.9951       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.37651E+01    ETASF =  0.87288E+00    WASF =  0.24254E-01
 Z = 0.75796            PR =   2.555            ETA = 0.76729
 PCN =   0.8460         CN = 0.84598            COMWK =  0.69540E+06
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.4000          DLP = 0.1017            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED: 1575.71      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.52711E+01    ETASF =  0.89655E+00    WASF =  0.17100E-01
 Z = 0.81898            PR =   4.920            ETA = 0.77176
 PCN =   0.8460         CN = 0.84598            COMWK =  0.13491E+07
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.52629          DLP = 0.3509
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000          DLP = 0.5649            WFB =   0.1298
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.12726E+03    ETASF =  0.10132E+01    TFSF =  0.19345E+02
 DHSF =  0.66310E+04
 TF =  401.006          ETA = 0.86181           CN =  2.869
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.71786E-02    ETASF =  0.10490E+01    TFSF =  0.40186E+01
 DHSF =  0.45558E+05
 TF =  223.379          ETA = 0.89214           CN =  2.128
 AUXWK =  0.19727E+07
 Additional Free Turbine Parameters:-
 Speed = 100.0%         Power =  0.19727E+07
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
 ETA =  0.5263          DLP = 0.0377     TOTHOT =   727.4669
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  0.1629         Exit Velocity =   91.77  Gross Thrust =    546.16
 Nozzle Coeff. =  0.97133E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

 Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
    1  0.00000     5.998   1.00000   1.00000  288.15  288.15     0.0  ******
    2  0.00000     5.998    ******   0.99510  ******  288.15  ******  ******
    3  0.00000     5.998    ******   2.54250  ******  403.23  ******  ******
    4  0.00000     5.997    ******   2.44080  ******  300.00  ******  ******
```

```
  5  0.00000    5.997   ******  12.00995  ******  521.44  ******  ******
  6  0.00000    4.798   ******  12.00995  ******  521.44  ******  ******
  7  0.00000    4.798   ******  11.65907  ******  702.17  ******  ******
  8  0.02706    4.928   ******  11.09420  ****** 1600.00  ******  ******
  9  0.02165    6.127   ******  11.09420  ****** 1408.70  ******  ******
 10  0.02165    6.127   ******   3.75507  ****** 1137.45  ******  ******
 11  0.02165    6.127   ******   3.71752  ****** 1137.45  ******  ******
 12  0.02165    6.127   ******   1.02865  ******  865.10  ******  ******
 13  0.02165    6.127   ******   1.01836  ******  865.10  ******  ******
 14  0.02165    6.127  1.00000   1.01836  861.37  865.10    91.8  0.1629
 15  0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
 16  0.02165    6.127   ******   0.99094  ******  727.47  ******  ******
 17  0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
 18  0.00000    1.199   ******  12.00995  ******  521.44  ******  ******

 Shaft Power =   1972743.75
  Net Thrust =   546.16
Equiv. Power =   2007958.63
  Fuel Flow =   0.1298
     S.F.C. =  65.8204
   E.S.F.C. =  64.6661
Sp. Sh. Power =    328926.38
Sp. Eq. Power =    334797.94
Sh. Th. Effy. =  0.3523
        Time Now 12:21:50
************************************************
-1
8 6 1650.0
-1
                              Time Now 12:21:50
************************************************
BERR( 1) =   -0.15940E-04
BERR( 2) =   -0.17055E-01
BERR( 3) =    0.21225E-01
BERR( 4) =    0.21709E-01
BERR( 5) =    0.66340E-01
BERR( 6) =    0.10030E+00
Loop   1
BERR( 1) =   -0.39913E-03
BERR( 2) =   -0.81953E-04
BERR( 3) =   -0.87970E-04
BERR( 4) =   -0.55908E-03
BERR( 5) =    0.57727E-02
BERR( 6) =    0.35586E-02
Loop   2
BERR( 1) =    0.33435E-04
BERR( 2) =    0.18144E-05
BERR( 3) =   -0.27187E-04
BERR( 4) =    0.32144E-05
BERR( 5) =    0.44748E-03
BERR( 6) =    0.38555E-03
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 0.9951       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.37651E+01     ETASF =  0.87288E+00     WASF =  0.24254E-01
Z = 0.74187             PR =   2.579             ETA = 0.76236
PCN =   0.8658          CN = 0.86584             COMWK =  0.73124E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000           DLP = 0.1026             WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1660.23      KWATTS
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***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.52711E+01    ETASF =  0.89655E+00    WASF =  0.17100E-01
Z = 0.82965           PR =   5.119          ETA = 0.76820
PCN =   0.8658        CN = 0.86584          COMWK =  0.14439E+07
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.51666         DLP = 0.3621
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000         DLP = 0.5837          WFB =   0.1411
***** TURBINE  1 PARAMETERS *****
CNSF =  0.12726E+03    ETASF =  0.10132E+01    TFSF =  0.19345E+02
DHSF =  0.66310E+04
TF =  400.548          ETA = 0.85858          CN =  2.892
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.71786E-02    ETASF =  0.10490E+01    TFSF =  0.40186E+01
DHSF =  0.45558E+05
TF =  223.609          ETA = 0.89044          CN =  2.094
AUXWK =  0.21722E+07

Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.21722E+07
*** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.5167          DLP = 0.0413     TOTHOT =   744.2617
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.1629         Exit Velocity =   97.28  Gross Thrust =    598.89
Nozzle Coeff. =  0.97135E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    6.197   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    6.197    ******   0.99510  ******  288.15  ******  ******
   3  0.00000    6.197    ******   2.56595  ******  405.26  ******  ******
   4  0.00000    6.197    ******   2.46331  ******  300.00  ******  ******
   5  0.00000    6.197    ******  12.61006  ******  529.23  ******  ******
   6  0.00000    4.958    ******  12.61006  ******  529.23  ******  ******
   7  0.00000    4.958    ******  12.24792  ******  713.85  ******  ******
   8  0.02846    5.099    ******  11.66424  ****** 1650.00  ******  ******
   9  0.02277    6.338    ******  11.66424  ****** 1451.89  ******  ******
  10  0.02277    6.338    ******   3.94370  ****** 1174.79  ******  ******
  11  0.02277    6.338    ******   3.90427  ****** 1174.79  ******  ******
  12  0.02277    6.338    ******   1.02987  ******  886.84  ******  ******
  13  0.02277    6.338    ******   1.01957  ******  886.84  ******  ******
  14  0.02277    6.338   1.00000   1.01957  882.68  886.84    97.3  0.1629
  15  0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  16  0.02277    6.338    ******   0.98856  ******  744.26  ******  ******
  17  0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  18  0.00000    1.239    ******  12.61006  ******  529.23  ******  ******

  Shaft Power =   2172153.75
   Net Thrust =   598.89
 Equiv. Power =   2210768.50
    Fuel Flow =   0.1411
       S.F.C. =  64.9530
     E.S.F.C. =  63.8185
Sp. Sh. Power =    350518.88
Sp. Eq. Power =    356750.09
Sh. Th. Effy. =   0.3570
        Time Now 12:21:50
*********************************************
-1
8 6 1700.0
-1
```

```
                              Time Now 12:21:50
 ***********************************************
 BERR( 1) =    0.33435E-04
 BERR( 2) =   -0.16578E-01
 BERR( 3) =    0.21080E-01
 BERR( 4) =    0.21294E-01
 BERR( 5) =    0.33898E-01
 BERR( 6) =    0.10102E+00
 Loop   1
 BERR( 1) =   -0.53726E-03
 BERR( 2) =   -0.91634E-03
 BERR( 3) =    0.12353E-02
 BERR( 4) =    0.57389E-03
 BERR( 5) =    0.67417E-02
 BERR( 6) =    0.87081E-02
 Loop   2
 BERR( 1) =   -0.13907E-04
 BERR( 2) =   -0.71833E-05
 BERR( 3) =   -0.45125E-04
 BERR( 4) =   -0.47654E-04
 BERR( 5) =    0.84975E-03
 BERR( 6) =    0.85971E-03
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0      I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 0.9951        Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.37651E+01     ETASF =  0.87288E+00     WASF =  0.24254E-01
 Z = 0.72236             PR =   2.603           ETA = 0.75668
 PCN =   0.8897          CN = 0.88974           COMWK =  0.77430E+06
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.4000           DLP = 0.1036            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED: 1761.68      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.52711E+01     ETASF =  0.89655E+00     WASF =  0.17100E-01
 Z = 0.83990             PR =   5.350           ETA = 0.76391
 PCN =   0.8897          CN = 0.88974           COMWK =  0.15597E+07
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.50544           DLP = 0.3767
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000           DLP = 0.6056            WFB =   0.1540
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.12726E+03     ETASF =  0.10132E+01     TFSF =  0.19345E+02
 DHSF =  0.66310E+04
 TF =  400.202           ETA = 0.85424           CN =  2.928
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.71786E-02     ETASF =  0.10490E+01     TFSF =  0.40186E+01
 DHSF =  0.45558E+05
 TF =  225.203           ETA = 0.89279           CN =  2.063
 AUXWK =  0.24046E+07
 Additional Free Turbine Parameters:-
 Speed = 100.0%          Power =  0.24046E+07
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
 ETA =  0.5054           DLP = 0.0456     TOTHOT =   760.4543
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  0.1629          Exit Velocity =  103.41  Gross Thrust =    662.24
 Nozzle Coeff. =  0.97139E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	6.439	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	6.439	******	0.99510	******	288.15	******	******
3	0.00000	6.439	******	2.59062	******	407.48	******	******
4	0.00000	6.439	******	2.48700	******	300.00	******	******
5	0.00000	6.439	******	13.30538	******	538.16	******	******
6	0.00000	5.151	******	13.30538	******	538.16	******	******
7	0.00000	5.151	******	12.92865	******	724.34	******	******
8	0.02991	5.305	******	12.32301	******	1700.00	******	******
9	0.02392	6.593	******	12.32301	******	1495.33	******	******
10	0.02392	6.593	******	4.13557	******	1211.33	******	******
11	0.02392	6.593	******	4.09421	******	1211.33	******	******
12	0.02392	6.593	******	1.03244	******	906.83	******	******
13	0.02392	6.593	******	1.02211	******	906.83	******	******
14	0.02392	6.593	1.00000	1.02211	902.15	906.83	103.4	0.1629
15	0.00000	0.000	******	0.00000	******	0.00	******	******
16	0.02392	6.593	******	0.98685	******	760.45	******	******
17	0.00000	0.000	******	0.00000	******	0.00	******	******
18	0.00000	1.288	******	13.30538	******	538.16	******	******

Shaft Power = 2404616.50
Net Thrust = 662.24
Equiv. Power = 2447316.00
Fuel Flow = 0.1540
S.F.C. = 64.0602
E.S.F.C. = 62.9426
Sp. Sh. Power = 373465.72
Sp. Eq. Power = 380097.47
Sh. Th. Effy. = 0.3620
Time Now 12:21:50
****
-1
8 6 1750.0
-1
Time Now 12:21:50
****
BERR(1) = -0.13907E-04
BERR(2) = -0.16141E-01
BERR(3) = 0.20817E-01
BERR(4) = 0.21111E-01
BERR(5) = 0.36488E-02
BERR(6) = 0.10328E+00
Loop 1
BERR(1) = 0.27639E-02
BERR(2) = 0.26731E-03
BERR(3) = 0.26347E-02
BERR(4) = 0.44604E-02
BERR(5) = 0.38795E-01
BERR(6) = 0.30546E-01
Loop 2
BERR(1) = -0.39932E-03
BERR(2) = -0.41423E-03
BERR(3) = -0.24171E-03
BERR(4) = 0.18348E-05
BERR(5) = -0.28837E-01
BERR(6) = 0.20483E-02
Loop 3
Loop 4
BERR(1) = 0.11705E-04
BERR(2) = -0.12120E-04
BERR(3) = 0.10275E-03
BERR(4) = -0.72136E-04
BERR(5) = 0.46393E-01
BERR(6) = -0.28742E-02

```
Loop   5
BERR( 1) =    0.26335E-05
BERR( 2) =   -0.79345E-06
BERR( 3) =    0.60942E-05
BERR( 4) =   -0.23377E-04
BERR( 5) =   -0.14973E-03
BERR( 6) =   -0.27454E-04
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   5 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 0.9951       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.37651E+01    ETASF =  0.87288E+00    WASF =  0.24254E-01
Z = 0.69612            PR =   2.628            ETA = 0.75182
PCN =   0.9177         CN = 0.91773            COMWK =  0.82444E+06
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.4000          DLP = 0.1046            WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED: 1879.41      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.52711E+01    ETASF =  0.89655E+00    WASF =  0.17100E-01
Z = 0.84768            PR =   5.627            ETA = 0.75889
PCN =   0.9177         CN = 0.91773            COMWK =  0.17047E+07
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.49226          DLP = 0.3958
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99000E+00
ETA = 0.99000          DLP = 0.6316            WFB =   0.1693
***** TURBINE  1 PARAMETERS *****
CNSF =  0.12726E+03    ETASF =  0.10132E+01    TFSF =  0.19345E+02
DHSF =  0.66310E+04
TF =  399.970          ETA = 0.84885           CN =  2.977
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.71786E-02    ETASF =  0.10490E+01    TFSF =  0.40186E+01
DHSF =  0.45558E+05
TF =  228.197          ETA = 0.89927           CN =  2.033
AUXWK =  0.26871E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.26871E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.4923          DLP = 0.0509     TOTHOT =   775.6108
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.1629         Exit Velocity =  110.30  Gross Thrust =    739.76
Nozzle Coeff. =  0.97142E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    6.735   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    6.735    ******   0.99510  ******  288.15  ******  ******
   3  0.00000    6.735    ******   2.61546  ******  409.61  ******  ******
   4  0.00000    6.735    ******   2.51085  ******  300.00  ******  ******
   5  0.00000    6.735    ******  14.12763  ******  548.64  ******  ******
   6  0.00000    5.388    ******  14.12763  ******  548.64  ******  ******
   7  0.00000    5.388    ******  13.73187  ******  733.33  ******  ******
   8  0.03142    5.557    ******  13.10025  ****** 1750.00  ******  ******
   9  0.02513    6.904    ******  13.10025  ****** 1539.09  ******  ******
  10  0.02513    6.904    ******   4.33687  ****** 1247.10  ******  ******
  11  0.02513    6.904    ******   4.29350  ****** 1247.10  ******  ******
  12  0.02513    6.904    ******   1.03407  ******  924.15  ******  ******
  13  0.02513    6.904    ******   1.02373  ******  924.15  ******  ******
  14  0.02513    6.904   1.00000   1.02373  918.84  924.15   110.3  0.1629
```

```
  15   0.00000    0.000    ******  0.00000  ******    0.00  ******  ******
  16   0.02513    6.904    ******  0.98320  ******  775.61  ******  ******
  17   0.00000    0.000    ******  0.00000  ******    0.00  ******  ******
  18   0.00000    1.347    ******  14.12763  ******  548.64  ******  ******

  Shaft Power =   2687111.25
   Net Thrust =   739.76
 Equiv. Power =   2734808.50
    Fuel Flow =   0.1693
       S.F.C. =  62.9922
     E.S.F.C. =  61.8936
Sp. Sh. Power =    398991.31
Sp. Eq. Power =    406073.53
Sh. Th. Effy. =   0.3681
        Time Now 12:21:50
************************************************
-1
8 6 1800.0
-1
                                        Time Now 12:21:50
************************************************
BERR( 1) =    0.26335E-05
BERR( 2) =   -0.15712E-01
BERR( 3) =    0.20518E-01
BERR( 4) =    0.21307E-01
BERR( 5) =    0.43554E-01
BERR( 6) =    0.10066E+00
Loop   1
BERR( 1) =    0.33871E-03
BERR( 2) =   -0.29356E-03
BERR( 3) =    0.17437E-03
BERR( 4) =   -0.35135E-03
BERR( 5) =    0.71461E-02
BERR( 6) =    0.36041E-02
Loop   2
BERR( 1) =   -0.24890E-06
BERR( 2) =    0.44939E-05
BERR( 3) =   -0.74215E-04
BERR( 4) =   -0.12833E-03
BERR( 5) =    0.39849E-03
BERR( 6) =    0.18521E-03
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 0.9951       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.37651E+01     ETASF =  0.87288E+00     WASF =  0.24254E-01
 Z = 0.67522            PR =   2.644             ETA = 0.74708
 PCN =   0.9388          CN = 0.93880            COMWK =  0.86233E+06
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.4000          DLP = 0.1052           WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED: 1968.54      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.52711E+01     ETASF =  0.89655E+00     WASF =  0.17100E-01
 Z = 0.85567            PR =   5.860             ETA = 0.75511
 PCN =   0.9388          CN = 0.93880            COMWK =  0.18214E+07
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.48292          DLP = 0.4088
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99000E+00
 ETA = 0.99000          DLP = 0.6520            WFB =   0.1829
 ***** TURBINE  1 PARAMETERS *****
```

```
CNSF =  0.12726E+03    ETASF =  0.10132E+01    TFSF =  0.19345E+02
DHSF =  0.66310E+04
TF =  399.616          ETA = 0.84578          CN =  3.003
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.71786E-02    ETASF =  0.10490E+01    TFSF =  0.40186E+01
DHSF =  0.45558E+05
TF =  228.619          ETA = 0.89844          CN =  2.003
AUXWK =  0.29334E+07
Additional Free Turbine Parameters:-
Speed = 100.0%         Power =  0.29334E+07
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.4829          DLP = 0.0555     TOTHOT =   792.6246
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  0.1629         Exit Velocity =  116.57  Gross Thrust =    807.97
Nozzle Coeff. =  0.97147E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000    6.952   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000    6.952    ******   0.99510  ******  288.15  ******  ******
   3  0.00000    6.952    ******   2.63077  ******  411.22  ******  ******
   4  0.00000    6.952    ******   2.52554  ******  300.00  ******  ******
   5  0.00000    6.952    ******  14.80053  ******  557.18  ******  ******
   6  0.00000    5.561    ******  14.80053  ******  557.18  ******  ******
   7  0.00000    5.561    ******  14.39176  ******  744.59  ******  ******
   8  0.03288    5.744    ******  13.73979  ****** 1800.00  ******  ******
   9  0.02631    7.135    ******  13.73979  ****** 1582.54  ******  ******
  10  0.02631    7.135    ******   4.53970  ****** 1284.60  ******  ******
  11  0.02631    7.135    ******   4.49430  ****** 1284.60  ******  ******
  12  0.02631    7.135    ******   1.03654  ******  945.62  ******  ******
  13  0.02631    7.135    ******   1.02618  ******  945.62  ******  ******
  14  0.02631    7.135   1.00000   1.02618  939.72  945.62   116.6  0.1629
  15  0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  16  0.02631    7.135    ******   0.98109  ******  792.62  ******  ******
  17  0.00000    0.000    ******   0.00000  ******    0.00  ******  ******
  18  0.00000    1.390    ******  14.80053  ******  557.18  ******  ******

  Shaft Power =   2933401.50
   Net Thrust =   807.97
 Equiv. Power =   2985497.25
    Fuel Flow =   0.1829
       S.F.C. =  62.3416
     E.S.F.C. =  61.2538
Sp. Sh. Power =    421966.00
Sp. Eq. Power =    429459.91
Sh. Th. Effy. =   0.3720
        Time Now 12:21:50
************************************************
-3
```

B.2 Input and result file for ICR LS2-ADIGT engine performance simulation

```
1
 TURBOMATCH SCHEME - Windows NT version (October 1999)
LIMITS:100 Codewords, 800 Brick Data Items, 50 Station Vector
15 BD Items printable by any call of:-
OUTPUT, OUTPBD, OUTPSV, PLOTIT, PLOTBD or PLOTSV
 Input "Program" follows
```

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!PERFORMANCE SIMULATION OF AN INTERCOOLED/RECUPERATED THREE-SPOOL AERODERIVATIVE!
!INDUSTRIAL GAS TURBINE                              !
!INSPIRED BY GE LMS100 ENGINE CORE                          !
!MODELLED BY BARINYIMA NKOI, JULY 2012                       !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

OD SI KE CT FP
 -1
 -1
INTAKE  S1-2      D1-4          R300
COMPRE  S2-3      D5-10         R301   V5  V6
PREMAS  S3-4,20   D12-15
DUCTER  S4-5      D16-19        R302
COMPRE  S5-6      D20-25        R303   V20 V21
PREMAS  S6-7,21   D26-29
HETCOL  S7-8      D30-33
BURNER  S8-9      D34-36        R304
MIXEES  S9,21,10
TURBIN  S10-11    D37-44,303           V38
MIXEES  S11,20,12
TURBIN  S12-13    D46-53,301           V47
TURBIN  S13-14    D55-63               V55 V56
HETHOT  S7,14,18  D64-67
DUCTER  S14-15    D68-71        R305
NOZCON  S15-16,1  D72           R306
PERFOR  S1,0,0    D55,74-76,306,300,304,0,0,0,0,0,0,0,0,0
CODEND

!INTAKE
 1 0.0        !INTAKE ALTITUDE
 2 0.0        !ISA DEVIATION
 3 0.0        !MACH NUMBER
 4 0.9951     !PRESSURE RECOVERY
!LP COMPRESSOR
 5 0.80       !Z PARAMETER
 6 -1.0       !ROTATIONAL SPEED N
 7 3.00       !PRESSURE RATIO
 8 0.875      !ISENTROPIC EFFICIENCY
 9 1.0        !ERROR SELECTION
 10 4.0       !MAP NUMBER
!PREMAS
 12 0.906     !BLEED TO COOL LPT BLADES
 13 0.0       !MASS FLOW LOSS
 14 1.0       !PRESSURE RECOVERY
 15 0.0       !PRESSURE LOSS
!DUCTER INTERCOOLER
 16  2.0      !INTERCOOLER
 17  0.03     !PRESSURE LOSS
 18  0.30     !EFFECTIVENESS
 19  100000.0   !LIMITING VALUE OF FUEL FLOW
!HP COMPRESSOR
 20 0.80      !SURGE MARGIN
 21 -1.0      !SPOOL SPEED
 22 14.05     !PRESSURE RATIO
 23 0.875     !EFFICIENCY
 24 1.0       !ERROR SELECTOR
 25 5.0       !COMPRESSOR MAP NUMBER
!PREMAS
 26 0.82      !BLEED TO COOL LPT BLADES
 27 0.0       !MASS FLOW LOSS
 28 1.0       !PRESSURE FACTOR
 29 0.0       !PRESSURE LOSS
```

```
!HETCOL
 30  0.01       !COLD SIDE PRESSURE LOSS
 31  0.75       !EFFECTIVENESS
 32  1.0        !TYPE:RECUPERATOR
 33  0.02       !MASS FLOW LEAKAGE
!BURNER
 34 0.05        !FRACTUAL PRESSURE LOSS
 35 0.998       !COMBUSTION EFFICIENCY
 36 -1.0        !FUEL FLOW

 !HP TURBINE
 37 0.0         !AUXILIARY POWER REQUIRED
 38 -1.0        !NON-DIMENSIONAL MASSFLOW
 39 -1.0        !NON-DIMENSIONAL SPEED
 40 0.89        !EFFICIENCY
 41 -1.0        !REL ROT SPEED (COMPRESSOR TURBINE)
 42 2.0         !COMPRESSOR NUMBER
 43 1.0         !TURBINE MAP NUMBER
 44 -1.0        !POWER LAW INDEX
 !          !HPC WORK
!IP TURBINE
 46 0.0         !AUXILIARY POWER REQUIRED
 47 -1.0        !NON-DIMENSIONAL MASS FLOW
 48 -1.0        !NON-DIMENSIONAL SPEED
 49 0.89        !EFFICIENCY
 50 -1.0        !REL ROT SPEED (COMPRESSOR TURBINE)
 51 1.0         !COMPRESSOR NUMBER
 52 4.0         !TURBINE MAP NUMBER
 53 -1.0        !POWER LAW INDEX
 !          !LPC WORK
!LP TURBINE
 55 100000000   !AUXILIARY POWER REQUIRED
 56 -1.0        !NON-DIMENSIONAL MASS FLOW
 57 -1.0        !NON-DIMENSIONAL SPEED
 58 0.90        !EFFICIENCY
 59 -1.0        !REL ROT SPEED (COMPRESSOR TURBINE)
 60 0.0         !COMPRESSOR NUMBER
 61 5.0         !TURBINE MAP NUMBER
 62 1000.0      !POWER LAW INDEX
 !  0.0         !COMP WORK
!HETHOT
 64  0.02       !HOT SIDE PRESSURE LOSS
 65  0.75       !EFFECTIVENESS
 66  1.0        !TYPE:RECUPERATOR
 67  0.02       !MASS FLOW LEAKAGE
!DUCTER
 68  0.0        !DUCTER
 69  0.01       !PRESSURE LOSS
 70  0.0
 71  100000.0
!CONVERGENT NOZZLE
 72 -1.0        !AIR FIXED
!PERFORMANCE
 !          !SHAFT POWER OUTPUT
 74 1.0         !PROPELLER EFFICIENCY
 75 0.0         !SCALING INDEX (0=NO SCALING)
 76 0.0         !REQUIRED THRUST
 -1
 1 2 215.5      !INLET MASS FLOW
 5 6 320.0      !INTERCOOLER OUTLET TEMPERATURE
 9 6 1730.0     !COMBUSTION OUTLET TEMPERATURE
 -1
                                Time Now 15:58:18
 ***********************************************
```

```
            The Units for this Run are as follows:-
Temperature = K   Pressure = Atmospheres   Length = metres
Area = sq metres  Mass Flow = kg/sec       Velocity = metres/sec
Force = Newtons   s.f.c.(Thrust) =  mg/N sec   s.f.c.(Power) = mug/J
Sp. Thrust =    N/kg/sec     Power =   Watts
    ***** DESIGN POINT ENGINE CALCULATIONS *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000       Mach No. =  0.00
Etar = 0.9951       Momentum Drag =       0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.20833E+01     ETASF =  0.10542E+01     WASF =  0.11998E+01
Z = 0.80000             PR =   3.000             ETA = 0.87500
PCN =   1.0000          CN = 1.00000             COMWK =  0.26283E+08
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.3000           DLP = 0.0896             WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED:59202.10      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.21117E+01     ETASF =  0.10852E+01     WASF =  0.13840E+01
Z = 0.80000             PR =  14.050             ETA = 0.87500
PCN =   1.0000          CN = 1.00000             COMWK =  0.80431E+08
HETYP =  1.0 HEUA =     202.083
HETYP =  1.0 HEUA =     194.553
HETYP =  1.0 HEUA =     194.900
HETYP =  1.0 HEUA =     194.884
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETAD =  0.75000E+00
ETA = 0.75000           DLP = 0.4069
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99800E+00
ETA = 0.99800           DLP = 2.0139             WFB =   5.0426
***** TURBINE  1 PARAMETERS *****
CNSF =  0.11089E+03     ETASF =  0.10365E+01     TFSF =  0.19441E+01
DHSF =  0.72424E+04
TF =  401.640           ETA = 0.89000            CN =  2.800
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.70758E+02     ETASF =  0.10449E+01     TFSF =  0.66997E+00
DHSF =  0.59437E+04
TF =  414.346           ETA = 0.89000            CN =  2.060
AUXWK =  0.00000E+00
***** TURBINE  3 PARAMETERS *****
CNSF = -0.72344E-02     ETASF =  0.10729E+01     TFSF =  0.24433E+00
DHSF =  0.74209E+05
TF =  219.627           ETA = 0.90000            CN =  2.200
AUXWK =  0.10000E+09
Additional Free Turbine Parameters:-
Speed = *****%          Power =  0.10000E+09
HETYP =  1.0 HEUA =     194.884
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETAD =  0.75000E+00 HEUA =      194.884 ETASF =  0.00000E+00
ETA =  0.7500           DLP = 0.0204     TOTHOT =   704.3835
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  6.8037          Exit Velocity =   63.14  Gross Thrust =  13523.64
Nozzle Coeff. =  0.97116E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1   0.00000  215.500   1.00000   1.00000  288.15  288.15    0.0  ******
   2   0.00000  215.500    ******   0.99510  ******  288.15  ******  ******
   3   0.00000  215.500    ******   2.98530  ******  409.17  ******  ******
   4   0.00000  195.243    ******   2.98530  ******  409.17  ******  ******
   5   0.00000  195.243    ******   2.89574  ******  320.00  ******  ******
```

```
  6  0.00000   195.243   ******  40.68519  ******  717.66  ******  ******
  7  0.00000   160.099   ******  40.68519  ******  717.66  ******  ******
  8  0.00000   160.099   ******  40.27834  ******  696.52  ******  ******
  9  0.03150   165.142   ******  38.26442  ****** 1730.00  ******  ******
 10  0.02583   200.286   ******  38.26442  ****** 1568.39  ******  ******
 11  0.02583   200.286   ******  12.26526  ****** 1249.20  ******  ******
 12  0.02340   220.543   ******  12.26526  ****** 1179.81  ******  ******
 13  0.02340   220.543   ******   8.09782  ****** 1081.34  ******  ******
 14  0.02340   220.543   ******   1.01938  ******  689.50  ******  ******
 15  0.02340   220.543   ******   1.00918  ******  689.50  ******  ******
 16  0.02340   220.543  1.00000   1.00918  687.70  689.50   63.1  6.8037
 17  0.00000     0.000  ******   0.00000  ******    0.00  ******  ******
 18  0.02340   220.543   ******   0.99899  ******  704.38  ******  ******
 19  0.00000     0.000  ******   0.00000  ******    0.00  ******  ******
 20  0.00000    20.257   ******   2.98530  ******  409.17  ******  ******
 21  0.00000    35.144   ******  40.68519  ******  717.66  ******  ******

 Shaft Power = 100000000.00
  Net Thrust = 13523.64
 Equiv. Power = 100871960.00
   Fuel Flow =   5.0426
      S.F.C. =  50.4259
    E.S.F.C. =  49.9901
Sp. Sh. Power =    464037.13
Sp. Eq. Power =    468083.34
Sh. Th. Effy. =   0.4599
        Time Now 15:58:18
************************************************
-1
9 6 1900.0      !OD CALCULATION: TET = 1900.0K
-1
                                    Time Now 15:58:18
************************************************
BERR( 1) =    0.00000E+00
BERR( 2) =   -0.56810E-01
BERR( 3) =    0.67688E-01
BERR( 4) =    0.65764E-01
BERR( 5) =    0.11482E+00
BERR( 6) =    0.10913E+00
BERR( 7) =    0.16698E+00
BERR( 8) =    0.61694E+00
Loop   1
BERR( 1) =    0.71359E-03
BERR( 2) =   -0.42671E-01
BERR( 3) =    0.37125E-01
BERR( 4) =    0.37369E-01
BERR( 5) =    0.58342E-01
BERR( 6) =    0.59060E-01
BERR( 7) =    0.14255E+00
BERR( 8) =    0.49967E+00
Loop   2
BERR( 1) =    0.31976E-02
BERR( 2) =   -0.26053E-01
BERR( 3) =    0.61279E-02
BERR( 4) =    0.60719E-02
BERR( 5) =    0.14218E-01
BERR( 6) =    0.99941E-02
BERR( 7) =    0.11036E+00
BERR( 8) =    0.34201E+00
Loop   3
BERR( 1) =    0.57236E-02
BERR( 2) =   -0.38678E-02
BERR( 3) =   -0.16213E-01
BERR( 4) =   -0.22116E-01
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 BERR( 5) =   -0.11395E-01
 BERR( 6) =   -0.27789E-01
 BERR( 7) =    0.47070E-01
 BERR( 8) =    0.10311E+00
 Loop   4
 BERR( 1) =   -0.38936E-02
 BERR( 2) =   -0.87800E-03
 BERR( 3) =    0.13006E-01
 BERR( 4) =    0.11397E-01
 BERR( 5) =    0.13540E-01
 BERR( 6) =    0.16811E-01
 BERR( 7) =    0.49138E-02
 BERR( 8) =    0.38979E-01
 Loop   5
 Loop   6
 BERR( 1) =    0.36490E-04
 BERR( 2) =   -0.19393E-04
 BERR( 3) =   -0.11343E-03
 BERR( 4) =   -0.25746E-04
 BERR( 5) =    0.19037E-03
 BERR( 6) =    0.64763E-04
 BERR( 7) =    0.43429E-03
 BERR( 8) =    0.82656E-03
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   6 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0      I.S.A. Dev. =    0.000       Mach No. =  0.00
 Etar = 0.9951        Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.20833E+01     ETASF =  0.10542E+01     WASF =  0.11998E+01
 Z = 0.73814             PR =   3.199            ETA = 0.82456
 PCN =   1.0884          CN = 1.08844            COMWK =  0.34110E+08
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.3000           DLP = 0.0955            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED:80060.00      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.21117E+01     ETASF =  0.10852E+01     WASF =  0.13840E+01
 Z = 0.83703             PR =  15.868            ETA = 0.84240
 PCN =   1.0521          CN = 1.05214            COMWK =  0.10191E+09
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.71383           DLP = 0.4676
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99800E+00
 ETA = 0.99800           DLP = 2.3314            WFB =   6.6542
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.11089E+03     ETASF =  0.10365E+01     TFSF =  0.19441E+01
 DHSF =  0.72424E+04
 TF =  401.550           ETA = 0.88844           CN =  2.813
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.70758E+02     ETASF =  0.10449E+01     TFSF =  0.66997E+00
 DHSF =  0.59437E+04
 TF =  415.595           ETA = 0.89410           CN =  2.138
 AUXWK =  0.00000E+00
 ***** TURBINE  3 PARAMETERS *****
 CNSF = -0.72344E-02     ETASF =  0.10729E+01     TFSF =  0.24433E+00
 DHSF =  0.74209E+05
 TF =  221.849           ETA = 0.90712           CN =  2.098
 AUXWK =  0.13557E+09
 Additional Free Turbine Parameters:-
 Speed = *****%          Power =  0.13557E+09
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
 ETA =  0.7138           DLP = 0.0285     TOTHOT =   747.3179
```

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***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  6.8037          Exit Velocity =   77.23  Gross Thrust =  18998.44
Nozzle Coeff. =  0.97127E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000   246.613   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000   246.613    ******   0.99510  ******  288.15  ******  ******
   3  0.00000   246.613    ******   3.18330  ******  425.27  ******  ******
   4  0.00000   223.432    ******   3.18330  ******  425.27  ******  ******
   5  0.00000   223.440    ******   3.08780  ******  320.00  ******  ******
   6  0.00000   223.440    ******  48.99620  ******  758.40  ******  ******
   7  0.00000   183.221    ******  48.99620  ******  758.40  ******  ******
   8  0.00000   183.221    ******  48.52861  ******  741.77  ******  ******
   9  0.03632   189.875    ******  46.19720  ****** 1900.00  ******  ******
  10  0.02978   230.094    ******  46.19720  ****** 1719.83  ******  ******
  11  0.02978   230.094    ******  14.70628  ****** 1374.84  ******  ******
  12  0.02698   253.276    ******  14.70628  ****** 1297.40  ******  ******
  13  0.02698   253.276    ******   9.61710  ****** 1188.51  ******  ******
  14  0.02698   253.276    ******   1.02559  ******  735.13  ******  ******
  15  0.02698   253.276    ******   1.01533  ******  735.13  ******  ******
  16  0.02698   253.276   1.00000   1.01533  732.44  735.13    77.2  6.8037
  17  0.00000     0.000    ******   0.00000  ******    0.00  ******  ******
  18  0.02698   253.276    ******   0.99709  ******  747.32  ******  ******
  19  0.00000     0.000    ******   0.00000  ******    0.00  ******  ******
  20  0.00000    23.182    ******   3.18330  ******  425.27  ******  ******
  21  0.00000    40.219    ******  48.99620  ******  758.40  ******  ******

  Shaft Power = 135569296.00
   Net Thrust = 18998.44
 Equiv. Power = 136794256.00
    Fuel Flow =   6.6542
       S.F.C. =  49.0832
     E.S.F.C. =  48.6437
Sp. Sh. Power =    549724.31
Sp. Eq. Power =    554691.44
Sh. Th. Effy. =  0.4724
         Time Now 15:58:18
************************************************
-1
9 6 1850.0      !OD CALCULATION: TET = 1850.0K
-1
                                Time Now 15:58:18
************************************************
BERR( 1) =    0.36490E-04
BERR( 2) =    0.15604E-01
BERR( 3) =   -0.17547E-01
BERR( 4) =   -0.21391E-01
BERR( 5) =   -0.29460E-01
BERR( 6) =   -0.33180E-01
BERR( 7) =   -0.56391E-01
BERR( 8) =   -0.15162E+00
Loop   1
BERR( 1) =    0.41205E-03
BERR( 2) =   -0.11552E-03
BERR( 3) =    0.76010E-03
BERR( 4) =    0.18547E-03
BERR( 5) =    0.10568E-02
BERR( 6) =    0.36252E-03
BERR( 7) =    0.70451E-02
BERR( 8) =    0.95822E-02
Loop   2
BERR( 1) =    0.35085E-04
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 BERR( 2) =   0.19183E-05
 BERR( 3) =   0.36163E-04
 BERR( 4) =  -0.40996E-05
 BERR( 5) =   0.15902E-04
 BERR( 6) =  -0.71634E-05
 BERR( 7) =  -0.43092E-02
 BERR( 8) =  -0.37126E-03
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000       Mach No. =  0.00
 Etar = 0.9951       Momentum Drag =       0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.20833E+01     ETASF =  0.10542E+01     WASF =  0.11998E+01
 Z = 0.75482             PR =   3.165             ETA = 0.83787
 PCN =   1.0681          CN = 1.06808             COMWK =  0.32313E+08
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.3000           DLP = 0.0945             WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED:75224.85      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.21117E+01     ETASF =  0.10852E+01     WASF =  0.13840E+01
 Z = 0.82676             PR =  15.391             ETA = 0.85229
 PCN =   1.0393          CN = 1.03932             COMWK =  0.96466E+08
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.72145           DLP = 0.4543
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99800E+00
 ETA = 0.99800           DLP = 2.2504             WFB =   6.2305
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.11089E+03     ETASF =  0.10365E+01     TFSF =  0.19441E+01
 DHSF =  0.72424E+04
 TF =  401.504           ETA = 0.88810            CN =  2.816
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.70758E+02     ETASF =  0.10449E+01     TFSF =  0.66997E+00
 DHSF =  0.59437E+04
 TF =  415.793           ETA = 0.89338            CN =  2.127
 AUXWK =  0.00000E+00
 ***** TURBINE  3 PARAMETERS *****
 CNSF = -0.72344E-02     ETASF =  0.10729E+01     TFSF =  0.24433E+00
 DHSF =  0.74209E+05
 TF =  222.119           ETA = 0.90966            CN =  2.128
 AUXWK =  0.12650E+09

 Additional Free Turbine Parameters:-
 Speed = *****%          Power =  0.12650E+09
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
 ETA =  0.7215           DLP = 0.0263     TOTHOT =   733.1089
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  6.8037          Exit Velocity =   73.31  Gross Thrust =  17527.60
 Nozzle Coeff. =  0.97123E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

 Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
    1  0.00000  239.941   1.00000   1.00000  288.15  288.15     0.0  ******
    2  0.00000  239.941    ******   0.99510  ******  288.15  ******  ******
    3  0.00000  239.941    ******   3.14990  ******  421.68  ******  ******
    4  0.00000  217.387    ******   3.14990  ******  421.68  ******  ******
    5  0.00000  217.394    ******   3.05541  ******  320.00  ******  ******
    6  0.00000  217.394    ******  47.02483  ******  747.02  ******  ******
    7  0.00000  178.263    ******  47.02483  ******  747.02  ******  ******
    8  0.00000  178.263    ******  46.57058  ******  725.86  ******  ******
```

```
  9   0.03495   184.494   ****** 44.32014  ****** 1850.00  ******  ******
  10   0.02866   223.625   ****** 44.32014  ****** 1675.36  ******  ******
  11   0.02866   223.625   ****** 14.09417  ****** 1337.44  ******  ******
  12   0.02597   246.179   ****** 14.09417  ****** 1262.49  ******  ******
  13   0.02597   246.179   ******  9.20586  ****** 1155.70  ******  ******
  14   0.02597   246.179   ******  1.02321  ******  717.72  ******  ******
  15   0.02597   246.179   ******  1.01298  ******  717.72  ******  ******
  16   0.02597   246.179  1.00000  1.01298  715.28  717.72   73.3  6.8037
  17   0.00000    0.000   ******  0.00000  ******    0.00  ******  ******
  18   0.02597   246.179   ******  0.99687  ******  733.11  ******  ******
  19   0.00000    0.000   ******  0.00000  ******    0.00  ******  ******
  20   0.00000   22.554   ******  3.14990  ******  421.68  ******  ******
  21   0.00000   39.131   ****** 47.02483  ******  747.02  ******  ******

  Shaft Power = 126500816.00
   Net Thrust = 17527.60
 Equiv. Power = 127630944.00
    Fuel Flow =   6.2305
       S.F.C. =  49.2530
     E.S.F.C. =  48.8168
Sp. Sh. Power =    527215.69
Sp. Eq. Power =    531925.69
Sh. Th. Effy. =   0.4708
        Time Now 15:58:18
************************************************
-1
9 6 1800.0
-1
                                   Time Now 15:58:18
************************************************
BERR( 1) =    0.35085E-04
BERR( 2) =    0.16022E-01
BERR( 3) =   -0.17850E-01
BERR( 4) =   -0.21973E-01
BERR( 5) =   -0.30405E-01
BERR( 6) =   -0.34184E-01
BERR( 7) =   -0.44102E-01
BERR( 8) =   -0.15946E+00
Loop   1
BERR( 1) =    0.93029E-03
BERR( 2) =   -0.80678E-04
BERR( 3) =   -0.14163E-02
BERR( 4) =   -0.24139E-02
BERR( 5) =    0.10331E-03
BERR( 6) =   -0.25354E-02
BERR( 7) =    0.31546E-02
BERR( 8) =    0.86826E-02
Loop   2
BERR( 1) =    0.49314E-04
BERR( 2) =   -0.10076E-04
BERR( 3) =    0.35848E-04
BERR( 4) =   -0.60880E-05
BERR( 5) =   -0.44310E-04
BERR( 6) =    0.19026E-04
BERR( 7) =   -0.46975E-03
BERR( 8) =   -0.16106E-02
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =   0.000      Mach No. =  0.00
Etar = 0.9951       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.20833E+01     ETASF =  0.10542E+01     WASF =  0.11998E+01
Z = 0.77252             PR =   3.102            ETA = 0.85302
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PCN =   1.0408         CN = 1.04080           COMWK =  0.29864E+08
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.3000          DLP = 0.0926           WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED:68671.11      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.21117E+01    ETASF =  0.10852E+01    WASF =  0.13840E+01
Z = 0.81673            PR =  14.880           ETA = 0.86238
PCN =   1.0245         CN = 1.02452           COMWK =  0.89985E+08
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.73228          DLP = 0.4355
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99800E+00
ETA = 0.99800          DLP = 2.1537           WFB =   5.7394
***** TURBINE  1 PARAMETERS *****
CNSF =  0.11089E+03    ETASF =  0.10365E+01    TFSF =  0.19441E+01
DHSF =  0.72424E+04
TF =  401.447          ETA = 0.88825          CN =  2.813
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.70758E+02    ETASF =  0.10449E+01    TFSF =  0.66997E+00
DHSF =  0.59437E+04
TF =  415.133          ETA = 0.89212          CN =  2.102
AUXWK =  0.00000E+00
***** TURBINE  3 PARAMETERS *****
CNSF = -0.72344E-02    ETASF =  0.10729E+01    TFSF =  0.24433E+00
DHSF =  0.74209E+05
TF =  221.015          ETA = 0.90609          CN =  2.158
AUXWK =  0.11553E+09
Additional Free Turbine Parameters:-
Speed = *****%         Power =  0.11553E+09
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.7323          DLP = 0.0239    TOTHOT =   720.8944
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  6.8037         Exit Velocity =   69.13  Gross Thrust =  15860.88
Nozzle Coeff. =  0.97119E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	230.501	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	230.501	******	0.99510	******	288.15	******	******
3	0.00000	230.501	******	3.08684	******	416.66	******	******
4	0.00000	208.834	******	3.08684	******	416.66	******	******
5	0.00000	208.844	******	2.99423	******	320.00	******	******
6	0.00000	208.844	******	44.55372	******	735.16	******	******
7	0.00000	171.252	******	44.55372	******	735.16	******	******
8	0.00000	171.252	******	44.11826	******	713.08	******	******
9	0.03351	176.991	******	41.96455	******	1800.00	******	******
10	0.02748	214.583	******	41.96455	******	1630.82	******	******
11	0.02748	214.583	******	13.35958	******	1300.37	******	******
12	0.02490	236.250	******	13.35958	******	1227.76	******	******
13	0.02490	236.250	******	8.75733	******	1124.26	******	******
14	0.02490	236.250	******	1.02065	******	705.02	******	******
15	0.02490	236.250	******	1.01044	******	705.02	******	******
16	0.02490	236.250	1.00000	1.01044	702.85	705.02	69.1	6.8037
17	0.00000	0.000	******	0.00000	******	0.00	******	******
18	0.02490	236.250	******	0.99676	******	720.89	******	******
19	0.00000	0.000	******	0.00000	******	0.00	******	******
20	0.00000	21.667	******	3.08684	******	416.66	******	******
21	0.00000	37.592	******	44.55372	******	735.16	******	******

```
Shaft Power = 115528736.00
Net Thrust = 15860.88
```

```
 Equiv. Power = 116551400.00
   Fuel Flow =   5.7394
      S.F.C. =  49.6793
    E.S.F.C. =  49.2434
Sp. Sh. Power =    501207.59
Sp. Eq. Power =    505644.28
Sh. Th. Effy. =   0.4668
        Time Now 15:58:18
***********************************************
-1
9 6 1750.0
-1
                                    Time Now 15:58:18
***********************************************
BERR( 1) =    0.49314E-04
BERR( 2) =    0.16433E-01
BERR( 3) =   -0.18337E-01
BERR( 4) =   -0.22510E-01
BERR( 5) =   -0.31256E-01
BERR( 6) =   -0.34924E-01
BERR( 7) =   -0.44865E-01
BERR( 8) =   -0.16462E+00
Loop   1
BERR( 1) =    0.18108E-03
BERR( 2) =    0.91738E-03
BERR( 3) =   -0.12741E-02
BERR( 4) =   -0.24317E-02
BERR( 5) =    0.52027E-03
BERR( 6) =   -0.23402E-02
BERR( 7) =    0.18766E-02
BERR( 8) =    0.37983E-02
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   1 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0      I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 0.9951       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.20833E+01     ETASF =  0.10542E+01     WASF =  0.11998E+01
Z = 0.78951             PR =   3.026             ETA = 0.86796
PCN =   1.0122          CN = 1.01223             COMWK =  0.27320E+08
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.3000           DLP = 0.0903             WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED:61910.96      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.21117E+01     ETASF =  0.10852E+01     WASF =  0.13840E+01
Z = 0.80724             PR =  14.378             ETA = 0.87053
PCN =   1.0093          CN = 1.00933             COMWK =  0.83632E+08
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.74427           DLP = 0.4154
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99800E+00
ETA = 0.99800           DLP = 2.0543             WFB =   5.2415
***** TURBINE  1 PARAMETERS *****
CNSF =  0.11089E+03     ETASF =  0.10365E+01     TFSF =  0.19441E+01
DHSF =  0.72424E+04
TF =  401.497           ETA = 0.88868            CN =  2.810
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.70758E+02     ETASF =  0.10449E+01     TFSF =  0.66997E+00
DHSF =  0.59437E+04
TF =  414.274           ETA = 0.89085            CN =  2.074
AUXWK =  0.00000E+00
***** TURBINE  3 PARAMETERS *****
```

```
CNSF = -0.72344E-02    ETASF =  0.10729E+01     TFSF =  0.24433E+00
DHSF =  0.74209E+05
TF =  219.541           ETA = 0.90022           CN =  2.189
AUXWK =  0.10398E+09
Additional Free Turbine Parameters:-
Speed = *****%          Power =  0.10398E+09
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.7443           DLP = 0.0214     TOTHOT =   710.4229
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  6.8037          Exit Velocity =   65.04  Gross Thrust =  14241.05
Nozzle Coeff. =  0.97126E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	220.175	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	220.175	******	0.99510	******	288.15	******	******
3	0.00000	220.175	******	3.01126	******	411.25	******	******
4	0.00000	199.479	******	3.01126	******	411.25	******	******
5	0.00000	199.515	******	2.92092	******	320.00	******	******
6	0.00000	199.515	******	41.99584	******	724.35	******	******
7	0.00000	163.602	******	41.99584	******	724.35	******	******
8	0.00000	163.602	******	41.58041	******	702.37	******	******
9	0.03204	168.844	******	39.52615	******	1750.00	******	******
10	0.02627	204.756	******	39.52615	******	1586.46	******	******
11	0.02627	204.756	******	12.55942	******	1262.59	******	******
12	0.02380	225.453	******	12.55942	******	1192.37	******	******
13	0.02380	225.453	******	8.27392	******	1092.50	******	******
14	0.02380	225.453	******	1.02492	******	694.84	******	******
15	0.02380	225.453	******	1.01467	******	694.84	******	******
16	0.02380	225.453	1.00000	1.01467	692.91	694.84	65.0	6.8037
17	0.00000	0.000	******	0.00000	******	0.00	******	******
18	0.02380	225.453	******	1.00356	******	710.42	******	******
19	0.00000	0.000	******	0.00000	******	0.00	******	******
20	0.00000	20.696	******	3.01126	******	411.25	******	******
21	0.00000	35.913	******	41.99584	******	724.35	******	******

```
  Shaft Power = 103975864.00
   Net Thrust = 14241.05
 Equiv. Power = 104894080.00
    Fuel Flow =   5.2415
       S.F.C. =  50.4103
     E.S.F.C. =  49.9690
Sp. Sh. Power =    472241.31
Sp. Eq. Power =    476411.72
Sh. Th. Effy. =   0.4600
      Time Now 15:58:18
************************************************
-1
9 6 1700.0
-1
                              Time Now 15:58:18
************************************************
BERR( 1) =    0.18108E-03
BERR( 2) =    0.17820E-01
BERR( 3) =   -0.20040E-01
BERR( 4) =   -0.25568E-01
BERR( 5) =   -0.31567E-01
BERR( 6) =   -0.38101E-01
BERR( 7) =   -0.43565E-02
BERR( 8) =   -0.16467E+00
Loop   1
BERR( 1) =    0.20707E-03
BERR( 2) =    0.40013E-02
```

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 BERR( 3) =   -0.81773E-02
 BERR( 4) =   -0.10274E-01
 BERR( 5) =   -0.17946E-01
 BERR( 6) =   -0.17345E-01
 BERR( 7) =    0.92005E-02
 BERR( 8) =   -0.16349E-01
 Loop   2
 BERR( 1) =    0.21185E-03
 BERR( 2) =    0.52689E-03
 BERR( 3) =   -0.41911E-02
 BERR( 4) =   -0.47251E-02
 BERR( 5) =   -0.97554E-02
 BERR( 6) =   -0.86366E-02
 BERR( 7) =    0.73171E-02
 BERR( 8) =    0.75275E-02
 Loop   3
 BERR( 1) =    0.85249E-04
 BERR( 2) =    0.17529E-03
 BERR( 3) =   -0.16858E-02
 BERR( 4) =   -0.17246E-02
 BERR( 5) =   -0.41027E-02
 BERR( 6) =   -0.34071E-02
 BERR( 7) =    0.24468E-02
 BERR( 8) =    0.74826E-03
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0      I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 0.9951        Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.20833E+01     ETASF =  0.10542E+01     WASF =  0.11998E+01
 Z = 0.81528             PR =   2.912            ETA = 0.88281
 PCN =   0.9629          CN = 0.96295            COMWK =  0.24007E+08
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.3000           DLP = 0.0869            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED:53277.80      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.21117E+01     ETASF =  0.10852E+01     WASF =  0.13840E+01
 Z = 0.79595             PR =  13.693            ETA = 0.87566
 PCN =   0.9852          CN = 0.98524            COMWK =  0.75420E+08
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.76245           DLP = 0.3863
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99800E+00
 ETA = 0.99800           DLP = 1.9241            WFB =   4.6420
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.11089E+03     ETASF =  0.10365E+01     TFSF =  0.19441E+01
 DHSF =  0.72424E+04
 TF =  401.796           ETA = 0.89216           CN =  2.782
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.70758E+02     ETASF =  0.10449E+01     TFSF =  0.66997E+00
 DHSF =  0.59437E+04
 TF =  412.147           ETA = 0.88784           CN =  2.002
 AUXWK =  0.00000E+00
 ***** TURBINE  3 PARAMETERS *****
 CNSF = -0.72344E-02     ETASF =  0.10729E+01     TFSF =  0.24433E+00
 DHSF =  0.74209E+05
 TF =  216.017           ETA = 0.88612           CN =  2.219
 AUXWK =  0.90185E+08
 Additional Free Turbine Parameters:-
 Speed = *****%          Power =  0.90185E+08
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
```

ETA = 0.7624 DLP = 0.0184 TOTHOT = 701.5080
***** CONVERGENT NOZZLE 1 PARAMETERS *****
NCOSF = 0.10000E+01
Area = 6.8037 Exit Velocity = 60.08 Gross Thrust = 12234.25
Nozzle Coeff. = 0.97118E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers = 1.0000

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	205.015	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	205.015	******	0.99510	******	288.15	******	******
3	0.00000	205.015	******	2.89807	******	404.37	******	******
4	0.00000	185.744	******	2.89807	******	404.37	******	******
5	0.00000	185.760	******	2.81113	******	320.00	******	******
6	0.00000	185.760	******	38.49180	******	712.15	******	******
7	0.00000	152.323	******	38.49180	******	712.15	******	******
8	0.00000	152.323	******	38.10551	******	695.48	******	******
9	0.03047	156.965	******	36.18142	******	1700.00	******	******
10	0.02499	190.402	******	36.18142	******	1541.90	******	******
11	0.02499	190.402	******	11.57707	******	1225.76	******	******
12	0.02264	209.673	******	11.57707	******	1157.73	******	******
13	0.02264	209.673	******	7.70477	******	1062.73	******	******
14	0.02264	209.673	******	1.02025	******	689.95	******	******
15	0.02264	209.673	******	1.01005	******	689.95	******	******
16	0.02264	209.673	1.00000	1.01005	688.29	689.95	60.1	6.8037
17	0.00000	0.000	******	0.00000	******	0.00	******	******
18	0.02264	209.673	******	1.00183	******	701.51	******	******
19	0.00000	0.000	******	0.00000	******	0.00	******	******
20	0.00000	19.271	******	2.89807	******	404.37	******	******
21	0.00000	33.437	******	38.49180	******	712.15	******	******

Shaft Power = 90184584.00
Net Thrust = 12234.25
Equiv. Power = 90973408.00
Fuel Flow = 4.6420
S.F.C. = 51.4721
E.S.F.C. = 51.0258
Sp. Sh. Power = 439892.25
Sp. Eq. Power = 443739.91
Sh. Th. Effy. = 0.4505
Time Now 15:58:18
****
-1
9 6 1650.0
-1
Time Now 15:58:18
****
BERR(1) = 0.85249E-04
BERR(2) = 0.17573E-01
BERR(3) = -0.20674E-01
BERR(4) = -0.25108E-01
BERR(5) = -0.36905E-01
BERR(6) = -0.39449E-01
BERR(7) = -0.10530E-01
BERR(8) = -0.16149E+00
Loop 1
BERR(1) = 0.26638E-03
BERR(2) = 0.67221E-02
BERR(3) = -0.78743E-02
BERR(4) = -0.95810E-02
BERR(5) = -0.14577E-01
BERR(6) = -0.14656E-01
BERR(7) = -0.51656E-03
BERR(8) = -0.54155E-01
Loop 2

```
BERR( 1) =   0.41446E-03
BERR( 2) =  -0.21035E-03
BERR( 3) =   0.33767E-03
BERR( 4) =   0.48068E-03
BERR( 5) =   0.11497E-02
BERR( 6) =   0.14043E-02
BERR( 7) =   0.61989E-02
BERR( 8) =   0.14724E-01
Loop   3
BERR( 1) =  -0.50759E-04
BERR( 2) =   0.23482E-04
BERR( 3) =   0.65628E-05
BERR( 4) =  -0.17371E-05
BERR( 5) =  -0.18816E-03
BERR( 6) =  -0.11043E-03
BERR( 7) =  -0.13640E-02
BERR( 8) =  -0.35995E-02
1
    ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 0.9951       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.20833E+01    ETASF =  0.10542E+01    WASF =  0.11998E+01
Z = 0.84214           PR =   2.764          ETA = 0.89551
PCN =   0.9027        CN = 0.90273          COMWK =  0.20431E+08
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.3000         DLP = 0.0825          WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED:44064.26     KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.21117E+01    ETASF =  0.10852E+01    WASF =  0.13840E+01
Z = 0.78359           PR =  12.979          ETA = 0.87780
PCN =   0.9587        CN = 0.95867          COMWK =  0.66850E+08
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.78429         DLP = 0.3533
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99800E+00
ETA = 0.99800         DLP = 1.7726          WFB =   4.0293
***** TURBINE  1 PARAMETERS *****
CNSF =  0.11089E+03    ETASF =  0.10365E+01    TFSF =  0.19441E+01
DHSF =  0.72424E+04
TF =  402.576         ETA = 0.89736         CN =  2.747
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.70758E+02    ETASF =  0.10449E+01    TFSF =  0.66997E+00
DHSF =  0.59437E+04
TF =  410.308         ETA = 0.88274         CN =  1.906
AUXWK =  0.00000E+00
***** TURBINE  3 PARAMETERS *****
CNSF = -0.72344E-02    ETASF =  0.10729E+01    TFSF =  0.24433E+00
DHSF =  0.74209E+05
TF =  212.636         ETA = 0.87429         CN =  2.250
AUXWK =  0.76556E+08
Additional Free Turbine Parameters:-
Speed = *****%        Power =  0.76556E+08
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.7843         DLP = 0.0154    TOTHOT =   693.2943
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  6.8037        Exit Velocity =   54.56  Gross Thrust =  10148.61
Nozzle Coeff. =  0.97107E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

```
Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000   187.535   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000   187.535    ******  0.99510  ******  288.15  ******  ******
   3  0.00000   187.535    ******  2.75050  ******  396.32  ******  ******
   4  0.00000   169.906    ******  2.75050  ******  396.32  ******  ******
   5  0.00000   169.898    ******  2.66799  ******  320.00  ******  ******
   6  0.00000   169.898    ****** 34.62895  ******  700.50  ******  ******
   7  0.00000   139.316    ****** 34.62895  ******  700.50  ******  ******
   8  0.00000   139.316    ****** 34.27565  ******  688.98  ******  ******
   9  0.02892   143.345    ****** 32.50301  ****** 1650.00  ******  ******
  10   0.02372   173.927    ******  32.50301  ****** 1497.46  ******  ******
  11   0.02372   173.927    ******  10.48043  ****** 1188.64  ******  ******
  12   0.02149   191.555    ******  10.48043  ****** 1122.75  ******  ******
  13   0.02149   191.555    ******   7.07573  ****** 1033.64  ******  ******
  14   0.02149   191.555    ******   1.01421  ******  685.51  ******  ******
  15   0.02149   191.555    ******   1.00407  ******  685.51  ******  ******
  16   0.02149   191.555   1.00000   1.00407  684.14  685.51    54.6  6.8037
  17   0.00000     0.000   ******   0.00000  ******    0.00  ******  ******
  18   0.02149   191.555    ******   0.99884  ******  693.29  ******  ******
  19   0.00000     0.000   ******   0.00000  ******    0.00  ******  ******
  20   0.00000    17.628    ******   2.75050  ******  396.32  ******  ******
  21   0.00000    30.582    ******  34.62895  ******  700.50  ******  ******

 Shaft Power =  76555640.00
  Net Thrust = 10148.61
 Equiv. Power =  77209992.00
   Fuel Flow =   4.0293
      S.F.C. =  52.6324
    E.S.F.C. =  52.1863
Sp. Sh. Power =    408221.44
Sp. Eq. Power =    411710.66
Sh. Th. Effy. =  0.4406
       Time Now 15:58:18
************************************************
-1
9 6 1600.0
-1
                                   Time Now 15:58:18
************************************************
BERR( 1) =   -0.50759E-04
BERR( 2) =    0.17954E-01
BERR( 3) =   -0.18824E-01
BERR( 4) =   -0.23626E-01
BERR( 5) =   -0.31870E-01
BERR( 6) =   -0.36254E-01
BERR( 7) =   -0.36589E-01
BERR( 8) =   -0.17043E+00
Loop   1
BERR( 1) =   -0.89383E-03
BERR( 2) =    0.54692E-02
BERR( 3) =   -0.51771E-02
BERR( 4) =   -0.78967E-02
BERR( 5) =   -0.16958E-01
BERR( 6) =   -0.14562E-01
BERR( 7) =   -0.78544E-02
BERR( 8) =   -0.50411E-01
Loop   2
BERR( 1) =   -0.25813E-02
BERR( 2) =   -0.16242E-02
BERR( 3) =    0.24314E-02
BERR( 4) =    0.90229E-03
BERR( 5) =   -0.49493E-02
BERR( 6) =   -0.11063E-02
BERR( 7) =    0.55593E-02
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 BERR( 8) =    0.95259E-02
 Loop   3
 BERR( 1) =    0.13112E-02
 BERR( 2) =    0.20429E-03
 BERR( 3) =   -0.26697E-03
 BERR( 4) =   -0.69012E-04
 BERR( 5) =    0.71663E-03
 BERR( 6) =    0.81011E-04
 BERR( 7) =    0.40056E-03
 BERR( 8) =    0.20558E-02
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 0.9951       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.20833E+01    ETASF =  0.10542E+01    WASF =  0.11998E+01
 Z = 0.86570            PR =   2.646            ETA = 0.90609
 PCN =   0.8485         CN = 0.84850            COMWK =  0.17640E+08
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.3000          DLP = 0.0790            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED:37028.46      KWATTS
 ***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.21117E+01    ETASF =  0.10852E+01    WASF =  0.13840E+01
 Z = 0.77371            PR =  12.284            ETA = 0.87904
 PCN =   0.9374         CN = 0.93738            COMWK =  0.59595E+08
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.80375          DLP = 0.3248
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99800E+00
 ETA = 0.99800          DLP = 1.6444            WFB =   3.5070
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.11089E+03    ETASF =  0.10365E+01    TFSF =  0.19441E+01
 DHSF =  0.72424E+04
 TF =  402.993          ETA = 0.90031           CN =  2.727
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.70758E+02    ETASF =  0.10449E+01    TFSF =  0.66997E+00
 DHSF =  0.59437E+04
 TF =  408.852          ETA = 0.87808           CN =  1.820
 AUXWK =  0.00000E+00
 ***** TURBINE  3 PARAMETERS *****
 CNSF = -0.72344E-02    ETASF =  0.10729E+01    TFSF =  0.24433E+00
 DHSF =  0.74209E+05
 TF =  209.988          ETA = 0.86002           CN =  2.284
 AUXWK =  0.64635E+08
 Additional Free Turbine Parameters:-
 Speed = *****%         Power =  0.64635E+08
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
 ETA =  0.8037          DLP = 0.0129     TOTHOT =   685.6708
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  6.8037          Exit Velocity =   49.90  Gross Thrust =   8531.59
 Nozzle Coeff. =  0.97115E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

 Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
    1  0.00000  172.324   1.00000   1.00000  288.15  288.15     0.0  ******
    2  0.00000  172.324    ******   0.99510  ******  288.15  ******  ******
    3  0.00000  172.324    ******   2.63266  ******  389.82  ******  ******
    4  0.00000  156.126    ******   2.63266  ******  389.82  ******  ******
    5  0.00000  156.331    ******   2.55368  ******  320.00  ******  ******
    6  0.00000  156.331    ******  31.36819  ******  689.08  ******  ******
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```
   7  0.00000   128.191    ******  31.36819  ******  689.08  ******  ******
   8  0.00000   128.191    ******  31.04335  ******  683.68  ******  ******
   9  0.02736   131.698    ******  29.39899  ****** 1600.00  ******  ******
  10   0.02243   159.837    ******  29.39899  ****** 1453.09  ******  ******
  11   0.02243   159.837    ******   9.51380  ****** 1151.44  ******  ******
  12   0.02033   176.036    ******   9.51380  ****** 1087.90  ******  ******
  13   0.02033   176.036    ******   6.48928  ****** 1003.58  ******  ******
  14   0.02033   176.036    ******   1.01872  ******  682.10  ******  ******
  15   0.02033   176.036    ******   1.00853  ******  682.10  ******  ******
  16   0.02033   176.036   1.00000   1.00853  680.96  682.10    49.9  6.8037
  17   0.00000     0.000    ******  0.00000  ******    0.00  ******  ******
  18   0.02033   176.036    ******   1.00586  ******  685.67  ******  ******
  19   0.00000     0.000    ******  0.00000  ******    0.00  ******  ******
  20   0.00000    16.198    ******   2.63266  ******  389.82  ******  ******
  21   0.00000    28.139    ******  31.36819  ******  689.08  ******  ******

  Shaft Power =  64635128.00
   Net Thrust =  8531.59
 Equiv. Power =  65185220.00
    Fuel Flow =   3.5070
       S.F.C. =  54.2578
     E.S.F.C. =  53.7999
Sp. Sh. Power =    375079.06
Sp. Eq. Power =    378271.25
Sh. Th. Effy. =   0.4274
        Time Now 15:58:19
************************************************
-1
9 6 1550.0
-1
                                    Time Now 15:58:19
************************************************
BERR( 1) =    0.13112E-02
BERR( 2) =    0.18679E-01
BERR( 3) =   -0.19238E-01
BERR( 4) =   -0.24187E-01
BERR( 5) =   -0.31673E-01
BERR( 6) =   -0.36635E-01
BERR( 7) =   -0.60032E-01
BERR( 8) =   -0.17920E+00
Loop   1
BERR( 1) =    0.15182E-02
BERR( 2) =    0.80513E-02
BERR( 3) =   -0.83633E-02
BERR( 4) =   -0.10623E-01
BERR( 5) =   -0.13919E-01
BERR( 6) =   -0.16383E-01
BERR( 7) =   -0.21969E-01
BERR( 8) =   -0.70636E-01
Loop   2
BERR( 1) =    0.28211E-02
BERR( 2) =   -0.96507E-04
BERR( 3) =   -0.22684E-03
BERR( 4) =   -0.43436E-03
BERR( 5) =   -0.17944E-04
BERR( 6) =   -0.12603E-02
BERR( 7) =    0.78450E-02
BERR( 8) =    0.19144E-01
Loop   3
BERR( 1) =    0.19741E-04
BERR( 2) =    0.51274E-04
BERR( 3) =   -0.79986E-04
BERR( 4) =   -0.57463E-04
BERR( 5) =    0.34240E-03
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 BERR( 6) =    0.15017E-04
 BERR( 7) =   -0.15786E-02
 BERR( 8) =   -0.30478E-02
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
 ***** AMBIENT AND INLET PARAMETERS *****
 Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
 Etar = 0.9951       Momentum Drag =      0.00
 ***** COMPRESSOR  1 PARAMETERS *****
 PRSF =  0.20833E+01    ETASF =  0.10542E+01    WASF =  0.11998E+01
 Z = 0.88379            PR =   2.514            ETA = 0.90522
 PCN =   0.7953         CN = 0.79533            COMWK =  0.15140E+08
 ***** DUCT/AFTER BURNING 1 PARAMETERS *****
 ETA =  0.3000          DLP = 0.0751            WFB =   0.0000
 DUCTER IS USED AS AN INTERCOOLER!
 ****INTERCOOLER****HEAT REMOVED:30882.94      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
 PRSF =  0.21117E+01    ETASF =  0.10852E+01    WASF =  0.13840E+01
 Z = 0.76462            PR =  11.580            ETA = 0.87904
 PCN =   0.9177         CN = 0.91772            COMWK =  0.52508E+08
 ***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
 ETA = 0.82463          DLP = 0.2956
 ***** COMBUSTION CHAMBER PARAMETERS *****
 ETASF =  0.99800E+00
 ETA = 0.99800          DLP = 1.5108            WFB =   3.0121
 ***** TURBINE  1 PARAMETERS *****
 CNSF =  0.11089E+03    ETASF =  0.10365E+01    TFSF =  0.19441E+01
 DHSF =  0.72424E+04
 TF =  403.340          ETA = 0.90262           CN =  2.711
 AUXWK =  0.00000E+00
 ***** TURBINE  2 PARAMETERS *****
 CNSF =  0.70758E+02    ETASF =  0.10449E+01    TFSF =  0.66997E+00
 DHSF =  0.59437E+04
 TF =  407.813          ETA = 0.87317           CN =  1.734
 AUXWK =  0.00000E+00
 ***** TURBINE  3 PARAMETERS *****
 CNSF = -0.72344E-02    ETASF =  0.10729E+01    TFSF =  0.24433E+00
 DHSF =  0.74209E+05
 TF =  207.972          ETA = 0.84295           CN =  2.319
 AUXWK =  0.53535E+08
 Additional Free Turbine Parameters:-
 Speed = *****%         Power =  0.53535E+08
 ***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
 ETA =  0.8246          DLP = 0.0107     TOTHOT =   677.9760
 ***** CONVERGENT NOZZLE  1 PARAMETERS *****
 NCOSF =  0.10000E+01
 Area =  6.8037         Exit Velocity =   45.18  Gross Thrust =   7025.18
 Nozzle Coeff. =  0.97104E+00
 Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

 Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
    1  0.00000  157.111   1.00000   1.00000  288.15  288.15     0.0  ******
    2  0.00000  157.111    ******   0.99510  ******  288.15  ******  ******
    3  0.00000  157.111    ******   2.50196  ******  383.89  ******  ******
    4  0.00000  142.343    ******   2.50196  ******  383.89  ******  ******
    5  0.00000  142.346    ******   2.42690  ******  320.00  ******  ******
    6  0.00000  142.346    ******  28.10434  ******  677.56  ******  ******
    7  0.00000  116.723    ******  28.10434  ******  677.56  ******  ******
    8  0.00000  116.723    ******  27.80877  ******  678.68  ******  ******
    9  0.02581  119.736    ******  26.29800  ****** 1550.00  ******  ******
   10  0.02116  145.358    ******  26.29800  ****** 1408.75  ******  ******
   11  0.02116  145.358    ******   8.53627  ****** 1114.40  ******  ******
   12  0.01917  160.126    ******   8.53627  ****** 1053.12  ******  ******
   13  0.01917  160.126    ******   5.86798  ******  972.96  ******  ******
```

```
  14  0.01917   160.126   ******   1.01238  ******  678.70  ******  ******
  15  0.01917   160.126   ******   1.00225  ******  678.70  ******  ******
  16  0.01917   160.126  1.00000   1.00225  677.76  678.70    45.2  6.8037
  17  0.00000     0.000  ******  0.00000  ******    0.00  ******  ******
  18  0.01917   160.126   ******   1.00172  ******  677.98  ******  ******
  19  0.00000     0.000  ******  0.00000  ******    0.00  ******  ******
  20  0.00000    14.768   ******   2.50196  ******  383.89  ******  ******
  21  0.00000    25.622   ****** 28.10434  ******  677.56  ******  ******

 Shaft Power =  53534644.00
  Net Thrust =  7025.18
Equiv. Power =  53987608.00
   Fuel Flow =   3.0121
      S.F.C. =  56.2650
    E.S.F.C. =  55.7929
Sp. Sh. Power =    340743.41
Sp. Eq. Power =    343626.47
Sh. Th. Effy. =  0.4121
        Time Now 15:58:19
***********************************************
-1
9 6 1500.0
-1
                                 Time Now 15:58:19
***********************************************
BERR( 1) =    0.19741E-04
BERR( 2) =    0.19119E-01
BERR( 3) =   -0.19269E-01
BERR( 4) =   -0.24716E-01
BERR( 5) =   -0.32556E-01
BERR( 6) =   -0.36786E-01
BERR( 7) =   -0.95340E-01
BERR( 8) =   -0.19654E+00
Loop   1
BERR( 1) =    0.15272E-03
BERR( 2) =    0.91124E-02
BERR( 3) =   -0.94097E-02
BERR( 4) =   -0.12063E-01
BERR( 5) =   -0.15017E-01
BERR( 6) =   -0.17635E-01
BERR( 7) =   -0.40578E-01
BERR( 8) =   -0.86187E-01
Loop   2
BERR( 1) =    0.39002E-03
BERR( 2) =   -0.34918E-03
BERR( 3) =   -0.12588E-03
BERR( 4) =   -0.41324E-03
BERR( 5) =    0.14655E-01
BERR( 6) =   -0.60461E-03
BERR( 7) =    0.16518E-01
BERR( 8) =    0.23931E-01
Loop   3
BERR( 1) =   -0.26972E-03
BERR( 2) =   -0.38773E-06
BERR( 3) =    0.63454E-04
BERR( 4) =   -0.22380E-04
BERR( 5) =   -0.48513E-02
BERR( 6) =    0.81908E-03
BERR( 7) =   -0.43446E-02
BERR( 8) =   -0.51142E-02
Loop   4
BERR( 1) =    0.34994E-04
BERR( 2) =    0.11878E-04
BERR( 3) =   -0.25106E-04
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BERR( 4) =    0.26489E-04
BERR( 5) =    0.68650E-04
BERR( 6) =   -0.17118E-03
BERR( 7) =    0.57057E-03
BERR( 8) =    0.51970E-03
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   4 Loops *****
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0     I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 0.9951       Momentum Drag =       0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.20833E+01    ETASF =  0.10542E+01    WASF =  0.11998E+01
Z = 0.89829            PR =   2.394            ETA = 0.89356
PCN =   0.7473         CN = 0.74733            COMWK =  0.13178E+08
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.3000          DLP = 0.0715            WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED:26207.59     KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.21117E+01    ETASF =  0.10852E+01    WASF =  0.13840E+01
Z = 0.75367            PR =  10.935            ETA = 0.87904
PCN =   0.8970         CN = 0.89699            COMWK =  0.46470E+08
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.82500          DLP = 0.2703
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99800E+00
ETA = 0.99800          DLP = 1.3948            WFB =   2.5904
***** TURBINE  1 PARAMETERS *****
CNSF =  0.11089E+03    ETASF =  0.10365E+01    TFSF =  0.19441E+01
DHSF =  0.72424E+04
TF =  403.911          ETA = 0.90571           CN =  2.693
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.70758E+02    ETASF =  0.10449E+01    TFSF =  0.66997E+00
DHSF =  0.59437E+04
TF =  407.127          ETA = 0.86729           CN =  1.657
AUXWK =  0.00000E+00
***** TURBINE  3 PARAMETERS *****
CNSF = -0.72344E-02    ETASF =  0.10729E+01    TFSF =  0.24433E+00
DHSF =  0.74209E+05
TF =  207.030          ETA = 0.82496           CN =  2.358
AUXWK =  0.43997E+08
Additional Free Turbine Parameters:-
Speed = *****%         Power =  0.43997E+08
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.8250          DLP = 0.0088     TOTHOT =   670.4169
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  6.8037         Exit Velocity =   41.05  Gross Thrust =   5829.70
Nozzle Coeff. =  0.97109E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000

Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area
   1  0.00000   143.640   1.00000   1.00000  288.15  288.15     0.0  ******
   2  0.00000   143.640    ******   0.99510  ******  288.15  ******  ******
   3  0.00000   143.640    ******   2.38189  ******  379.31  ******  ******
   4  0.00000   130.138    ******   2.38189  ******  379.31  ******  ******
   5  0.00000   130.143    ******   2.31043  ******  320.00  ******  ******
   6  0.00000   130.143    ******  25.26479  ******  666.50  ******  ******
   7  0.00000   106.717    ******  25.26479  ******  666.50  ******  ******
   8  0.00000   106.717    ******  24.99444  ******  673.74  ******  ******
   9  0.02427   109.307    ******  23.59964  ****** 1500.00  ******  ******
  10   0.01990   132.733    ******  23.59964  ****** 1364.52  ******  ******
  11   0.01990   132.733    ******   7.67942  ****** 1077.14  ******  ******
```

```
   12  0.01803  146.235   ******   7.67942  ****** 1018.32  ******  ******
   13  0.01803  146.235   ******   5.29413  ******  941.34  ******  ******
   14  0.01803  146.235   ******   1.01508  ******  675.10  ******  ******
   15  0.01803  146.235   ******   1.00493  ******  675.10  ******  ******
   16  0.01803  146.235  1.00000   1.00493  674.32  675.10   41.1  6.8037
   17  0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
   18  0.01803  146.235   ******   1.00627  ******  670.42  ******  ******
   19  0.00000    0.000   ******   0.00000  ******    0.00  ******  ******
   20  0.00000   13.502   ******   2.38189  ******  379.31  ******  ******
   21  0.00000   23.426   ******  25.26479  ******  666.50  ******  ******

  Shaft Power =  43996764.00
   Net Thrust =  5829.70
 Equiv. Power =  44372644.00
    Fuel Flow =   2.5904
       S.F.C. =  58.8778
     E.S.F.C. =  58.3791
Sp. Sh. Power =    306298.50
Sp. Eq. Power =    308915.34
Sh. Th. Effy. =  0.3938
        Time Now 15:58:19
************************************************
-1
9 6 1450.0
-1
                              Time Now 15:58:19
************************************************
BERR( 1) =    0.34994E-04
BERR( 2) =    0.19661E-01
BERR( 3) =   -0.19246E-01
BERR( 4) =   -0.25317E-01
BERR( 5) =   -0.39113E-01
BERR( 6) =   -0.38105E-01
BERR( 7) =   -0.14290E+00
BERR( 8) =   -0.21440E+00
Loop   1
BERR( 1) =    0.60995E-03
BERR( 2) =    0.90692E-02
BERR( 3) =   -0.99939E-02
BERR( 4) =   -0.12622E-01
BERR( 5) =   -0.12194E-01
BERR( 6) =   -0.18504E-01
BERR( 7) =   -0.56771E-01
BERR( 8) =   -0.87880E-01
Loop   2
BERR( 1) =    0.15607E-02
BERR( 2) =    0.10787E-02
BERR( 3) =   -0.45416E-02
BERR( 4) =   -0.39509E-02
BERR( 5) =    0.55256E-02
BERR( 6) =   -0.31167E-02
BERR( 7) =    0.16150E-01
BERR( 8) =    0.17252E-01
Loop   3
BERR( 1) =    0.27913E-03
BERR( 2) =    0.35057E-03
BERR( 3) =   -0.16732E-02
BERR( 4) =   -0.11530E-02
BERR( 5) =   -0.19048E-02
BERR( 6) =   -0.56733E-03
BERR( 7) =   -0.32713E-02
BERR( 8) =   -0.30282E-02
1
   ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   3 Loops *****
```

```
***** AMBIENT AND INLET PARAMETERS *****
Alt. =      0.0    I.S.A. Dev. =    0.000      Mach No. =  0.00
Etar = 0.9951       Momentum Drag =      0.00
***** COMPRESSOR  1 PARAMETERS *****
PRSF =  0.20833E+01    ETASF =  0.10542E+01    WASF =  0.11998E+01
Z = 0.91692            PR =   2.300            ETA = 0.88178
PCN =   0.7077         CN = 0.70769            COMWK =  0.11649E+08
***** DUCT/AFTER BURNING 1 PARAMETERS *****
ETA =  0.3000          DLP = 0.0687            WFB =   0.0000
DUCTER IS USED AS AN INTERCOOLER!
****INTERCOOLER****HEAT REMOVED:22667.80      KWATTS
***** COMPRESSOR  2 PARAMETERS *****
PRSF =  0.21117E+01    ETASF =  0.10852E+01    WASF =  0.13840E+01
Z = 0.74116            PR =  10.285            ETA = 0.87494
PCN =   0.8742         CN = 0.87415            COMWK =  0.41452E+08
***** HEAT EXCHANGER COLD SIDE PARAMETERS *****
ETA = 0.82500          DLP = 0.2493
***** COMBUSTION CHAMBER PARAMETERS *****
ETASF =  0.99800E+00
ETA = 0.99800          DLP = 1.2928            WFB =   2.2400
***** TURBINE  1 PARAMETERS *****
CNSF =  0.11089E+03    ETASF =  0.10365E+01    TFSF =  0.19441E+01
DHSF =  0.72424E+04
TF =  404.847          ETA = 0.91022           CN =  2.668
AUXWK =  0.00000E+00
***** TURBINE  2 PARAMETERS *****
CNSF =  0.70758E+02    ETASF =  0.10449E+01    TFSF =  0.66997E+00
DHSF =  0.59437E+04
TF =  406.576          ETA = 0.86103           CN =  1.597
AUXWK =  0.00000E+00
***** TURBINE  3 PARAMETERS *****
CNSF = -0.72344E-02    ETASF =  0.10729E+01    TFSF =  0.24433E+00
DHSF =  0.74209E+05
TF =  207.201          ETA = 0.80554           CN =  2.400
AUXWK =  0.36188E+08
Additional Free Turbine Parameters:-
Speed = *****%         Power =  0.36188E+08
***** HEAT EXCHANGER HOT SIDE PARAMETERS *****
ETA =  0.8250          DLP = 0.0074     TOTHOT =   662.0754
***** CONVERGENT NOZZLE  1 PARAMETERS *****
NCOSF =  0.10000E+01
Area =  6.8037         Exit Velocity =   37.38  Gross Thrust =   4877.05
Nozzle Coeff. =  0.97101E+00
Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area
1	0.00000	132.099	1.00000	1.00000	288.15	288.15	0.0	******
2	0.00000	132.099	******	0.99510	******	288.15	******	******
3	0.00000	132.099	******	2.28856	******	375.79	******	******
4	0.00000	119.682	******	2.28856	******	375.79	******	******
5	0.00000	119.715	******	2.21991	******	320.00	******	******
6	0.00000	119.715	******	22.83067	******	656.35	******	******
7	0.00000	98.166	******	22.83067	******	656.35	******	******
8	0.00000	98.166	******	22.58137	******	666.76	******	******
9	0.02282	100.406	******	21.28853	******	1450.00	******	******
10	0.01871	121.955	******	21.28853	******	1320.49	******	******
11	0.01871	121.955	******	6.93489	******	1039.38	******	******
12	0.01695	134.372	******	6.93489	******	983.19	******	******
13	0.01695	134.372	******	4.77332	******	908.54	******	******
14	0.01695	134.372	******	1.01075	******	668.83	******	******
15	0.01695	134.372	******	1.00064	******	668.83	******	******
16	0.01695	134.372	1.00000	1.00064	668.18	668.83	37.4	6.8037
17	0.00000	0.000	******	0.00000	******	0.00	******	******
18	0.01695	134.372	******	1.00335	******	662.08	******	******

```
  19   0.00000    0.000    ******  0.00000  ******   0.00  ******  ******
  20   0.00000   12.417    ******  2.28856  ******  375.79  ******  ******
  21   0.00000   21.549    ******  22.83067  ******  656.35  ******  ******

 Shaft Power =  36187584.00
  Net Thrust =  4877.05
 Equiv. Power =  36502040.00
   Fuel Flow =   2.2400
      S.F.C. =  61.9001
    E.S.F.C. =  61.3668
Sp. Sh. Power =    273942.78
Sp. Eq. Power =    276323.25
Sh. Th. Effy. =   0.3746
        Time Now 15:58:19
***********************************************
-3
```

Appendix C ADIGT-CHP model result files

C.1 Result of SC SS-ADIGT-CHP model performance

COMBINED-HEAT-AND-POWER PERFORMANCE FOR SC SS-ADIGT-CHP

AVERAGE LHV OF FUEL(natural gas)MJ/kg : 47.141

STEAM PRESSURE: 10.0 Bar SUPERHEATED STEAM TEMPERATURE: 673 K

TET (K)	Heat input (MW)	Exh gas Temp T4 (K)	Exh gas flow wg (kg/s)	steam flow ws (kg/s)	Economiser duty (kW)	Exh gas exit Temp T1(K)	HRSG duty (MW)	Shaft Power(MW)	GT Efficiency	Heat:Power ratio	Sup. heat. Duty (kW)	Temp drop in sup. ΔT_{sy}	Evap duty (kW)	Heat rate (MJ/MWs)	CHP efficiency
1500	5.810	884.9	5.653	1.100	334.741	422.1	3.107	1.567	0.296	2.09	530.074	78.949	2198.232	3.708	0.561
1350	4.197	832.0	4.790	0.812	247.301	428.5	2.295	0.980	0.256	2.46	391.611	68.834	1624.022	4.282	0.529
1400	4.697	851.0	5.063	0.904	275.148	426.2	2.554	1.157	0.270	2.32	435.707	72.467	1806.887	4.060	0.542
1450	5.217	869.6	5.330	0.998	303.920	424.0	2.821	1.341	0.282	2.21	481.269	76.023	1995.835	3.890	0.553
1500	5.808	885.5	5.651	1.101	335.067	422.1	3.110	1.563	0.295	2.10	530.591	79.064	2200.375	3.717	0.561
1550	6.350	906.9	5.881	1.205	366.783	419.5	3.404	1.757	0.303	2.04	580.815	83.155	2408.655	3.615	0.573
1600	6.892	928.9	6.074	1.307	397.944	416.8	3.694	1.944	0.309	2.00	630.159	87.362	2613.286	3.546	0.580
1650	7.447	953.5	6.253	1.418	431.729	413.9	4.007	2.130	0.314	1.98	683.660	92.066	2835.154	3.497	0.589
1700	8.054	976.4	6.462	1.535	467.387	411.1	4.338	2.340	0.319	1.95	740.125	96.444	3069.318	3.442	0.596
1750	8.737	996.5	6.718	1.660	505.327	408.7	4.690	2.591	0.325	1.91	800.205	100.287	3318.471	3.373	0.602
1800	9.407	1020.3	6.925	1.789	544.518	405.8	5.054	2.824	0.329	1.88	862.265	104.838	3575.833	3.331	0.608

C.2 Result of RC SS-ADIGT-CHP model performance

COMBINED-HEAT-AND-POWER PERFORMANCE FOR RC SS-ADIGT-CHP

AVERAGE LHV OF FUEL(natural gas)MJ/kg : 47.141

STEAM PRESSURE: 10.0 Bar | SUPERHEATED STEAM TEMPERATURE: 673 K

TET (K)	Heat input (MW)	Exh gas Temp T4 (K)	Exh gas flow wg (kg/s)	steam flow ws (kg/s)	Economiser duty (kW)	Exh gas exit Temp T1(K)	HRSG duty (MW)	Shaft Power(MW)	GT Efficiency	Heat:Power ratio	Sup. heat. Duty (kW)	Temp drop in sup. ΔT_{4Y}	Evap duty (kW)	Heat rate (MJ/MWs)	CHP efficiency
1500	5.095	900.6	5.638	1.138	346.567	420.2	3.217	1.567	0.337	2.16	548.802	81.958	2275.895	3.251	0.713
1350	3.527	848.9	4.744	0.842	256.392	426.5	2.380	0.961	0.299	2.61	406.007	72.058	1683.719	3.670	0.714
1400	4.009	866.4	5.032	0.935	284.612	424.4	2.642	1.149	0.314	2.42	450.693	75.415	1869.036	3.489	0.716
1450	4.505	885.4	5.307	1.033	314.587	422.1	2.920	1.337	0.325	2.30	498.160	79.044	2065.881	3.369	0.722
1500	5.091	901.3	5.635	1.140	346.904	420.2	3.220	1.564	0.337	2.17	549.335	82.079	2278.108	3.254	0.723
1550	5.608	921.7	5.871	1.244	378.578	417.7	3.514	1.762	0.344	2.10	599.493	85.976	2486.112	3.182	0.724
1600	6.097	945.4	6.058	1.351	411.290	414.8	3.818	1.949	0.350	2.06	651.293	90.517	2700.927	3.129	0.726
1650	6.599	970.2	6.239	1.464	445.705	411.8	4.137	2.137	0.355	2.04	705.790	95.253	2926.930	3.088	0.731
1700	7.164	993.2	6.451	1.584	482.192	409.1	4.476	2.351	0.360	2.00	763.569	99.656	3166.541	3.047	0.733
1750	7.814	1013.7	6.707	1.711	520.990	406.6	4.836	2.604	0.365	1.96	825.007	103.576	3421.326	3.001	0.735
1800	8.431	1037.7	6.914	1.843	560.945	403.7	5.207	2.840	0.369	1.93	888.278	108.173	3683.711	2.969	0.737

C.3 Result of ICR SS-ADIGT-CHP model performance

COMBINED-HEAT-AND-POWER PERFORMANCE FOR ICR SS-ADIGT-CHP

AVERAGE LHV OF FUEL(natural gas)MJ/kg : 47.141

STEAM PRESSURE: 10.0 Bar SUPERHEATED STEAM TEMPERATURE: 673 K

TET (K)	Heat input (MW)	Exh gas Temp T4 (K)	Exh gas flow wg (kg/s)	steam flow ws (kg/s)	Economiser duty (kW)	Exh gas exit Temp T1(K)	HRSG duty (MW)	Shaft Power(MW)	GT Efficiency	Heat:Power ratio	Sup. heat. Duty (kW)	Temp drop in sup. ΔT_{4Y}	Evap duty (kW)	Heat rate (MJ/MWs)	CHP efficiency
1500	5.059	826.4	5.637	0.941	286.501	429.2	2.659	1.567	0.340	1.79	453.685	67.763	1881.445	3.229	0.599
1350	3.314	789.5	4.501	0.673	204.920	433.7	1.902	0.884	0.292	2.27	324.499	60.708	1345.707	3.750	0.601
1400	3.834	801.9	4.865	0.756	230.173	432.2	2.136	1.091	0.312	2.06	364.487	63.079	1511.536	3.514	0.604
1450	4.399	815.8	5.226	0.846	257.654	430.5	2.392	1.309	0.326	1.92	408.005	65.737	1692.006	3.361	0.608
1500	5.052	827.3	5.630	0.942	286.877	429.1	2.663	1.563	0.339	1.79	454.281	67.935	1883.914	3.232	0.609
1550	5.620	844.0	5.922	1.038	315.896	427.1	2.932	1.781	0.347	1.73	500.233	71.129	2074.477	3.156	0.61
1600	6.121	865.1	6.127	1.135	345.409	424.5	3.206	1.973	0.353	1.71	546.968	75.163	2268.292	3.103	0.615
1650	6.651	886.8	6.338	1.239	377.028	421.9	3.500	2.172	0.358	1.70	597.037	79.312	2475.929	3.062	0.624
1700	7.262	906.8	6.593	1.350	411.062	419.5	3.815	2.405	0.363	1.67	650.933	83.136	2699.435	3.020	0.630
1750	7.980	924.2	6.904	1.471	447.706	417.4	4.156	2.687	0.369	1.63	708.959	86.463	2940.072	2.970	0.631
1800	8.621	945.6	7.135	1.592	484.555	414.8	4.498	2.933	0.373	1.61	767.311	90.555	3182.057	2.939	0.637

C.4 Result of SC LS1-ADIGT-CHP model performance

COMBINED-HEAT-AND-POWER PERFORMANCE FOR SC LS1-ADIGT-CHP

AVERAGE LHV OF FUEL (Natural gas)MJ/kg : 47.141

STEAM PRESSURE: 10.0 Bar   SUPERHEATED STEAM TEMPERATURE: 583 K

TET	Heat input (MW)	Exh gas Temp T4 (K)	Exh gas flow wg (kg/s)	steam flow ws (kg/s)	Economiser duty (kW)	Exh gas exit Temp T1(K)	HRSG duty (MW)	Shaft Power(MW)	GT Efficiency	Heat:Power ratio	Sup. heat. Duty (kW)	Temp drop in sup. ΔT_4	Evap duty (kW)	Heat rate (MJ/MWs)	CHP efficiency
1550	117.362	742.6	127.490	17.598	5357.116	436.6	46.336	43.850	0.410	1.11	5094.956	33.649	35180.028	2.676	0.653
1700	142.088	809.5	131.485	22.636	6890.716	427.9	59.600	53.924	0.416	1.16	6553.508	41.967	45251.141	2.635	0.706
1650	133.824	787.2	130.272	20.944	6375.698	430.8	55.146	50.581	0.414	1.15	6063.693	39.192	41869.032	2.646	0.690
1600	125.560	765.2	128.933	19.277	5868.362	433.7	50.758	47.175	0.412	1.13	5581.184	36.448	38537.369	2.662	0.672
1550	117.004	743.9	126.973	17.610	5360.822	436.5	46.368	43.593	0.408	1.12	5098.482	33.810	35204.370	2.684	0.653
1500	107.439	724.1	125.235	16.101	4901.478	439.0	42.395	38.704	0.395	1.15	4661.616	31.342	32187.866	2.776	0.630
1450	96.465	705.1	120.249	14.293	4351.044	441.5	37.634	33.762	0.384	1.17	4138.119	28.976	28573.185	2.857	0.606
1400	85.419	691.3	112.510	12.586	3831.352	443.3	33.139	28.992	0.372	1.20	3643.859	27.270	25160.382	2.946	0.585
1350	74.690	679.4	104.012	11.004	3349.954	444.9	28.975	24.361	0.358	1.25	3186.019	25.791	21999.055	3.066	0.564

C.5 Result of IC LS1-ADIGT-CHP model performance

COMBINED-HEAT-AND-POWER PERFORMANCE FOR IC LS1-ADIGT-CHP

AVERAGE LHV OF FUEL (Natural gas)MJ/kg : 47.141

STEAM PRESSURE: 10.0 Bar | SUPERHEATED STEAM TEMPERATURE: 583 K

TET	Heat input (MW)	Exh gas Temp T4 (K)	Exh gas flow wg (kg/s)	steam flow ws (kg/s)	Economiser duty (kW)	Exh gas exit Temp T1(K)	HRSG duty (MW)	Shaft Power(MW)	GT Efficiency	Heat:Power ratio	Sup. heat. Duty (kW)	Temp drop in sup. ΔT_{4Y}	Evap duty (kW)	Heat rate (MJ/MWs)	CHP efficiency
1550	114.209	657.1	127.423	12.032	3662.781	447.8	31.681	43.850	0.421	0.76	3483.537	23.019	24053.383	2.605	0.504
1700	134.866	715.4	130.473	16.198	4931.055	440.2	42.651	53.103	0.432	0.85	4689.745	30.265	32382.098	2.540	0.582
1650	127.427	697.0	128.986	14.801	4505.567	442.6	38.970	49.767	0.428	0.82	4285.079	27.972	29587.929	2.560	0.560
1600	119.748	678.6	127.071	13.388	4075.460	445.0	35.250	46.328	0.424	0.80	3876.020	25.683	26763.430	2.585	0.535
1550	113.105	659.2	126.118	12.042	3665.802	447.5	31.707	43.288	0.420	0.77	3486.410	23.276	24073.220	2.613	0.507
1500	106.789	643.0	125.234	10.923	3325.310	449.6	28.762	39.749	0.408	0.76	3162.580	21.263	21837.214	2.687	0.475
1450	99.119	626.6	122.535	9.659	2940.493	451.8	25.433	36.003	0.398	0.74	2796.595	19.217	19310.136	2.753	0.443
1400	93.278	609.5	121.871	8.547	2601.942	454.0	22.505	32.303	0.380	0.73	2474.611	17.097	17086.878	2.888	0.398
1350	86.240	595.1	119.518	7.501	2283.378	455.9	19.750	28.190	0.358	0.74	2171.637	15.299	14994.880	3.059	0.356

C.6 Result of ICR LS1-ADIGT-CHP model performance

COMBINED-HEAT-AND-POWER PERFORMANCE FOR ICR LS1-ADIGT-CHP

AVERAGE LHV OF FUEL (Natural gas)MJ/kg : 47.141

STEAM PRESSURE: 10.0 Bar SUPERHEATED STEAM TEMPERATURE: 583 K

TET	Heat input (MW)	Exh gas Temp T4 (K)	Exh gas flow wg (kg/s)	steam flow ws (kg/s)	Economiser duty (kW)	Exh gas exit Temp T1(K)	HRSG duty (MW)	Shaft Power(MW)	GT Efficiency	Heat:Power ratio	Sup. heat. Duty (kW)	Temp drop in sup. ΔT_{4Y}	Evap duty (kW)	Heat rate (MJ/MWs)	CHP efficiency
1550	114.077	665.2	127.420	12.554	3821.754	446.7	33.056	43.850	0.421	0.79	3634.730	24.018	25097.348	2.602	0.514
1700	133.555	723.5	130.921	16.796	5113.041	439.1	44.225	53.236	0.437	0.87	4862.826	31.275	33577.197	2.509	0.603
1650	126.163	705.2	129.070	15.348	4672.224	441.5	40.412	49.770	0.432	0.85	4443.581	28.988	30682.363	2.535	0.579
1600	119.045	686.7	127.282	13.937	4242.694	443.9	36.697	46.361	0.427	0.83	4035.071	26.693	27861.653	2.568	0.551
1550	112.997	667.1	126.378	12.577	3828.566	446.5	33.115	43.333	0.420	0.80	3641.209	24.260	25142.088	2.608	0.518
1500	106.958	650.9	125.548	11.456	3487.445	448.6	30.164	39.749	0.407	0.80	3316.781	22.244	22901.951	2.691	0.483
1450	102.301	630.9	125.937	10.203	3106.015	451.2	26.865	36.849	0.395	0.77	2954.016	19.750	20397.110	2.776	0.439
1400	95.296	616.0	123.757	9.090	2767.103	453.2	23.934	32.503	0.374	0.78	2631.690	17.905	18171.488	2.932	0.397
1350	88.309	601.3	121.320	8.002	2435.909	455.1	21.069	28.308	0.351	0.78	2316.703	16.079	15996.544	3.120	0.354

C.7 Result of SC LS2-ADIGT-CHP model performance

COMBINED HEAT AND POWER PERFORMANCE

AVERAGE LHV OF FUEL (Natural gas)MJ/kg 47.141

STEAM PRESSURE: 10.0 Bar SUPERHEATED STEAM TEMPERATURE: 655 K

TET	Heat input (MW)	Exh gas Temp T4 (K)	Exh gas flow wg (kg/s)	steam flow ws (kg/s)	Economiser duty (kW)	Exh gas exit Temp T1(K)	HRSG duty (MW)	Shaft Power(MW)	GT efficiency	Heat:Power ratio	Sup. heat. Duty (kW)	Temp drop in sup. ΔT_{4Y}	Evap duty (kW)	heat rate MJ/MWs	CHP efficiency
1730	239.943	783.3	220.590	32.847	9999.213	433.8	91.550	100.000	0.457	0.96	14572.517	55.624	65664.553	2.399	0.671
1900	324.561	836.4	257.910	44.961	13687.089	427.3	125.315	140.430	0.474	0.94	19947.103	65.121	89882.730	2.311	0.706
1850	299.378	816.9	248.240	40.960	12468.997	429.7	114.162	129.150	0.473	0.93	18171.897	61.637	81883.554	2.318	0.695
1800	274.196	800.3	237.330	37.266	11344.521	431.8	103.867	117.290	0.469	0.93	16533.123	58.656	74499.151	2.338	0.685
1750	249.866	787.7	225.890	34.114	10384.854	433.3	95.080	104.970	0.461	0.95	15134.536	56.414	68197.042	2.380	0.675
1700	221.242	782.6	208.410	30.964	9426.160	433.9	86.303	89.781	0.445	1.01	13737.369	55.500	61901.329	2.464	0.667
1650	194.673	776.7	191.490	27.913	8497.200	434.6	77.798	76.101	0.429	1.08	12383.534	54.451	55800.875	2.558	0.658
1600	172.489	767.1	177.850	25.104	7642.012	435.8	69.968	65.200	0.414	1.13	11137.211	52.727	50184.879	2.646	0.647
1545	151.620	756.9	165.240	22.521	6855.698	437.1	62.769	54.766	0.396	1.21	9991.263	50.912	45021.176	2.768	0.633
1500	136.016	747.2	155.570	20.483	6235.427	438.3	57.090	47.237	0.381	1.27	9087.301	49.184	40947.874	2.879	0.619
1450	120.483	736.1	145.980	18.445	5615.085	439.6	51.410	39.742	0.362	1.36	8183.236	47.200	36874.105	3.032	0.603

C.8 Result of IC LS2-ADIGT-CHP model performance

COMBINED-HEAT-AND-POWER PERFORMANCE FOR IC LS2-ADIGT-CHP

AVERAGE LHV OF FUEL (Natural gas)MJ/kg : 47.141

STEAM PRESSURE: 10.0 Bar | SUPERHEATED STEAM TEMPERATURE: 655 K

TET	Heat input (MW)	Exh gas Temp T4 (K)	Exh gas flow wg (kg/s)	steam flow ws (kg/s)	Economiser duty (kW)	Exh gas exit Temp T1(K)	HRSG duty (MW)	Shaft Power(MW)	GT efficiency	Heat:Power ratio	Sup. heat. Duty (kW)	Temp drop in sup. ΔT_{4Y}	Evap duty (kW)	Heat rate (MJ/MWs)	CHP efficiency
1730	234.262	691.6	220.469	23.160	7050.317	445.1	64.550	100.000	0.468	0.68	10274.895	39.241	46299.236	2.343	0.513
1900	310.159	739.7	252.319	32.307	9834.725	439.2	90.044	135.010	0.477	0.70	14332.797	47.829	64584.363	2.297	0.548
1850	289.493	721.4	245.480	29.285	8915.053	441.4	81.623	126.160	0.478	0.68	12992.499	44.564	58544.905	2.295	0.536
1800	266.267	707.8	235.575	26.576	8090.159	443.1	74.071	115.350	0.475	0.68	11790.325	42.141	53127.845	2.308	0.526
1750	242.941	697.5	224.731	24.241	7379.366	444.4	67.563	103.820	0.469	0.69	10754.440	40.294	48460.091	2.340	0.518
1700	216.033	692.1	209.039	22.010	6700.325	445.0	61.346	90.186	0.458	0.72	9764.829	39.332	44000.848	2.395	0.512
1650	188.347	687.5	191.007	19.694	5995.232	445.6	54.890	76.663	0.446	0.75	8737.249	38.516	39370.517	2.457	0.507
1600	165.036	683.4	175.748	17.776	5411.359	446.1	49.545	64.972	0.432	0.80	7886.332	37.783	35536.242	2.540	0.501
1550	142.743	679.9	159.940	15.903	4841.242	446.5	44.325	53.935	0.414	0.87	7055.463	37.143	31792.301	2.647	0.493
1500	123.674	676.2	146.149	14.277	4346.332	447.0	39.794	44.417	0.394	0.94	6334.198	36.493	28542.241	2.784	0.482
1450	107.378	669.8	134.274	12.705	3867.649	447.7	35.411	36.594	0.374	1.02	5636.581	35.346	25398.740	2.934	0.468

C.9 Result of ICR LS2-ADIGT-CHP model performance

COMBINED-HEAT-AND-POWER PERFORMANCE FOR ICR LS2 -ADIGT-CHP

AVERAGE LHV OF FUEL (Natural gas)MJ/kg : 47.141

STEAM PRESSURE: 10.0 Bar   SUPERHEATED STEAM TEMPERATURE: 655 K

TET	Heat input (MW)	Exh gas Temp T4 (K)	Exh gas flow wg (kg/s)	steam flow ws (kg/s)	Economiser duty (kW)	Exh gas exit Temp T1(K)	HRSG duty (MW)	Shaft Power(MW)	GT efficiency	Heat:Power ratio	Sup. heat. Duty (kW)	Temp drop in sup. ΔT_{4Y}	Evap duty (kW)	Heat rate (MJ/MWs)	CHP efficiency
1730	237.713	704.4	220.543	24.516	7463.127	443.5	68.330	100.000	0.461	0.719	10876.510	41.525	49010.144	2.377	0.522
1900	313.686	747.3	253.276	33.357	10154.548	438.2	92.972	135.570	0.474	0.722	14798.896	49.198	66684.631	2.314	0.553
1850	293.712	733.1	246.179	30.749	9360.592	440.0	85.703	126.500	0.472	0.713	13641.811	46.659	61470.743	2.322	0.544
1800	270.561	720.9	236.250	28.128	8562.647	441.5	78.397	115.530	0.468	0.714	12478.914	44.475	56230.665	2.342	0.535
1750	247.090	710.4	225.453	25.713	7827.580	442.8	71.667	103.980	0.464	0.726	11407.651	42.604	51403.496	2.376	0.527
1700	218.829	701.5	209.673	23.020	7007.658	443.9	64.160	90.185	0.452	0.749	10212.725	41.012	46019.095	2.426	0.518
1650	189.945	693.3	191.555	20.277	6172.827	444.9	56.516	76.556	0.442	0.777	8996.070	39.543	40536.779	2.481	0.511
1600	165.323	685.7	176.036	17.993	5477.392	445.8	50.149	64.635	0.429	0.817	7982.567	38.181	35969.880	2.558	0.502
1550	141.993	678.0	160.126	15.778	4803.035	446.7	43.975	53.535	0.413	0.865	6999.781	36.807	31541.392	2.652	0.491
1500	122.114	670.4	146.235	13.880	4225.378	447.7	38.686	43.997	0.395	0.926	6157.924	35.456	27747.939	2.776	0.478
1450	105.596	662.1	134.372	12.218	3719.410	448.7	34.054	36.188	0.376	0.991	5420.542	33.966	24425.258	2.918	0.461

Appendix D Techno-economic model calculations and results for ADIGT-CHP case studies

D.1 LSRCP conventional case annual cost model calculation

$\text{Boiler capital cost} = \text{number of boilers } \times \text{cost per kW}_{\text{th}} \times \text{Boiler capacity (kW}_{\text{th}})$

$$= 2 \times 80 \frac{£}{\text{kW}_{\text{th}}} \times 23.804\text{kW}_{\text{th}} = £3{,}808{,}722$$

$\text{Boiler O\&M cost}, C_{Bo/m} = \text{annual steam consumption (kWh}_{\text{th}}) \times \text{O\&M cost per kWh}_{\text{th}}$

$$= 208527507.6 \text{ kWh}_{\text{th}} \times 0.004 \frac{£}{\text{kWh}_{\text{th}}} = £834{,}110$$

$\text{Boiler fuel cost}, C_{Bh} = \text{annual steam consumption (kWh}_{\text{th}}) \times \text{fuel price per kWh}_{\text{th}}$

$$= 208527507.6 \text{ kWh}_{\text{th}} \times 0.05 \frac{£}{\text{kWh}_{\text{th}}} = £10{,}426{,}375$$

$\text{Grid electricity cost}, C_{Ge} = \text{annual electricity consumption (kWhe)} \times \text{grid electricity tariff per kWhe}$

$$= 2584200000 \text{ kWhe} \times 0.1 \frac{£}{\text{kWhe}} = £258420000$$

$\text{Boiler emission cost}, C_{Bemtx} = \text{annual heat consumption (kWh}_{\text{th}}) \times \text{emission tax per kWh}_{\text{th}}$

$$= 208527507.6 \text{ kWh}_{\text{th}} \times 0.002 \frac{£}{\text{kWh}_{\text{th}}} = £417055$$

$\text{Year 1 annual operation cost} = £834{,}110 + £10{,}426{,}375 + £258420000 + £417055$= £269263430

$\text{Present value of year (1) annual operation cost}$ = £244,784,937, utilising the formula $\frac{F_t}{(1+d)^t}$

$Loan, L = \text{Boiler capital cost} + \text{year 1 annual operation cost} = £273{,}072{,}152$

Applying Equation 6-10

Equal annual Loan repayment, $C_{Lr} = (L \text{ x } r)/[1-(1+r)^{-N}]$

$= (273{,}072{,}152 \text{ x } 0.05)/[1-(1+0.05)^{-10}]$ = £35,364,093

D.2 SC LS-ADIGT-CHP case annual cash flow model calculation (LSRCP CHP)

$\text{Initial cash flow}, F_0$
$$= (3 \times 100\text{MW GT} + 1 \times 43.85\text{MW GT}) \times \text{capital cost per kW} + \text{cost of 1 boiler}$$

$$\text{Initial cash flow}, F_0 = (3 \times 100000\text{kW} + 1 \times 43850\text{kW}) \times \frac{700£}{\text{kW}} + 23805\text{kW} \times 80\ £/\text{kW}$$

$$\text{Initial cash flow } F_0 = £242{,}599{,}361$$

Loan = initial cash flow = £242,599,361

Year 1 annual net cash flow of SC LS-ADIGT-CHP case for LSRCP:

$$\text{Annual Operation \& maintenance cost, } C_{o/m} = \text{total annual energy generated (kWh)} \times \text{O\&M cost per kWh}$$

$$= (\text{annual electricity generated kWhe} + \text{CHP steam generated kWhth}) \times \text{O\&M variable cost per kWh} + \text{Boiler steam generated kWhth} \times \text{O\&M cost per kWh} + \text{CHP fixed O\&M cost}$$

$$= (2586982563 + 355119227.35 + 386478173.45)\text{kWh} \times 0.02\text{£/kWh} + 10426375.38 \text{ kWh} \times 0.004\text{£/kWh} + 1719250) = \text{£}68{,}332{,}555$$

$$\text{Annual GT fuel cost, } C_f = \text{total annual power generated (kWh)} \times \text{fuel price per kWh} = (2942101790.35)\text{kWh} \times 0.05\text{£/kWh} = \text{£}147{,}105{,}090$$

$$\text{Annual grid electricity cost during outages of CHP, } C_{Ge} = \text{annual grid electricity consumption (kWhe)} \times \text{electricity tariff per kWhe}$$

$$= 129210000\text{kWhe} \times 0.1\text{£/kWhe} = \text{£}12{,}274{,}950$$

$$\text{Annual boiler heat cost during outages of CHP, } C_{Bh} = \text{annual heat generated in boiler(kWht)} \times \text{gas oil price per kWht}$$

$$= 10426375.38\text{kWht} \times 0.05\text{£/kWht} = \text{£}521{,}319$$

$$\text{Annual emission tax, } C_{emtx} = (\text{annual total ADIGT emissions })\text{kg} \times \text{emission tax rate per kg} + \text{Boiler emission cost}$$

$$= (2745391762.62)\text{kg} \times 0.005\text{£/kg} + 5025.51 = \text{£}13{,}731{,}984$$

$$\text{Annual saved electricity cost, } C_e = \text{annual electricity consumption from CHP (kWhe)} \times \text{electricity tariff per kWhe}$$

$$= 2454990000 \text{ kWhe} \times 0.1\text{£/kWhe} = \text{£}245499000$$

$$\text{Annual saved heat cost, } C_h = \text{annual heat consumption from CHP(kWht)} \times \text{gas oil price per kWht} = 198101132.22\text{kWht} \times 0.05\text{£/kWht} = \text{£}9{,}905{,}057$$

$$\text{Annual revenue from excess electricity exported to grid, } R_e = \text{annual electricity exported (kWhe)} \times \text{electricity tariff per kWhe} = 487111790.35\text{kWhe} \times 0.05\text{£/kWhe} = \text{£}24{,}355{,}590$$

$$\text{Annual revenue from excess steam exported, } R_h = \text{annual steam exported (kWht)} \times \text{gas oil price per kWht} = 188377041.24 \text{ kWht} \times \frac{0.025\text{£}}{\text{kWht}} = \text{£}4{,}709{,}426$$

$$\text{Year 1 annual net cash flow, } F_1 = C_e + C_h + R_e + R_h - C_{0/m} - C_f - C_{bh} - C_{Ge} - C_{emtx}$$

$$= 245{,}499{,}000 + 9{,}905{,}057 + 24{,}355{,}590 + 4{,}709{,}426 - 68{,}332{,}555 - 147{,}105{,}090 - 521{,}319 - 12{,}274{,}950 - 13{,}731{,}984 = \text{£}41{,}857{,}125$$

$$\text{Present value of year 1 annual net cash flow } = \frac{F_1}{(1+d)^1}$$

$$\text{Present value of year 1 annual net cash flow } = \frac{41{,}857{,}125}{(1+0.1)^1}$$

$$\text{Present value of year 1 annual net cash flow } = \text{£}38{,}051{,}932$$

Applying Equation 6-10

Equal annual Loan repayment, $\mathrm{C_{Lr}} = (\mathrm{L \; x \; r})/[1-(1+\mathrm{r})^{-\mathrm{N}}]$

$$\mathrm{C_{Lr}} = (242{,}599{,}361 \text{ x } 0.05)/[1-(1+0.05)^{-10}]$$

Annual loan repayment $\mathrm{C_{Lr}} = £31{,}417{,}727$

D.2.1 Simple payback period for SC LS-ADIGT-CHP case of LSRCP:

$$\text{Simple payback period } \mathrm{SPBP_{SC\_CHP}} = \frac{\text{initial cash flow of SC ADIGTCHP case}}{\text{conventional case annual running cost} - \text{SC ADIGTCHP case annual running cost}}$$

$$\text{Simple payback period } \mathrm{SPBP_{SC\_CHP}} = \frac{242599360.80}{244784936.72 - 194133574.40}$$

$$\text{Simple payback period } \mathrm{SPBP_{SC\_CHP}} = 4.8 \text{ years}$$

D.2.2 Net present value for SC LS-ADIGT-CHP case of LSRCP:

$$\text{Net present value } \mathrm{NPV_{SC\_CHP}} = \text{Total life cycle present value} - \text{initial cash flow of SC ADIGTCHP}$$

$$\text{Net present value } \mathrm{NPV_{SC\_CHP}} = 483792325.60 - 242599360.80 = £241{,}192{,}965$$

D.2.3 Simple payback period for IC LS-ADIGT-CHP case of LSRCP:

$$\mathrm{SPBP_{IC\_CHP}} = \frac{\text{initial cash flow of IC ADIGTCHP case}}{\text{conventional case annual running cost} - \text{IC ADIGTCHP case annual running cost}}$$

$$\mathrm{SPBP_{IC\_CHP}} = \frac{244318611}{244784937 - 191829644} = 4.6 \text{ years}$$

D.2.4 Net present value for IC LS-ADIGT-CHP case of LSRCP:

$$\mathrm{NPV_{IC\_CHP}} = \text{Total life cycle present value} - \text{initial cash flow of IC ADIGTCHP}$$

$$\mathrm{NPV_{IC\_CHP}} = 504075884 - 244318611 = £259{,}757{,}273$$

D.2.5 Simple payback period for ICR LS-ADIGT-CHP case of LSRCP

$$\mathrm{SPBP_{ICR\_CHP}} = \frac{\text{initial cash flow of ICR ADIGTCHP case}}{\text{conventional case running cost} - \text{ICR ADIGTCHP case running cost}}$$

$$\mathrm{SPBP_{ICR\_CHP}} = \frac{246037861}{244784937 - 192294919} = 4.7 \text{ years}$$

D.2.6 Net present value for ICR LS-ADIGT-CHP case of LSRCP:

$$\mathrm{NPV_{ICR\_CHP}} = \text{Total life cycle present value} - \text{initial cash flow of ICR ADIGTCHP}$$

$$\mathrm{NPV_{ICR\_CHP}} = 498053892 - 246037861 = £252{,}016{,}032$$

D.3 SSRP conventional case annual cost model calculation

$$\text{Boiler capital cost} = \text{number of boilers } \times \text{cost per kW}_{\text{th}} \times \text{Boiler capacity (kW}_{\text{th}})$$

$$= 2 \times 80 \frac{£}{\text{kW}_{\text{th}}} \times 547.515\text{kW}_{\text{th}} = £87{,}602$$

$$C_{Bo/m} = \text{annual steam consumption (kWh}_{\text{th}}) \times \text{O\&M cost per kWh}_{\text{th}}$$

$$= 4796231.4 \text{ kWh}_{\text{th}} \times 0.004 \frac{£}{\text{kWh}_{\text{th}}} = £19{,}185$$

$$C_{Bh} = \text{annual steam consumption (kWh}_{\text{th}}) \times \text{fuel price per kWh}_{\text{th}}$$

$$= 4796231.4 \text{ kWh}_{\text{th}} \times 0.05 \frac{£}{\text{kWh}_{\text{th}}} = £239{,}812$$

$$C_{Ge} = \text{annual electricity consumption (kWhe)} \times \text{grid electricity tariff per kWhe}$$

$$= 52560000 \text{ kWhe} \times 0.1 \frac{£}{\text{kWhe}} = £5256000$$

$$C_{Bemtx} = \text{annual steam consumption (kWh}_{\text{th}}) \times \text{emission tax per kWh}_{\text{th}}$$

$$= 4796231.4 \text{ kWh}_{\text{th}} \times 0.002 \frac{£}{\text{kWh}_{\text{th}}} = £9593$$

Year 1 annual operation cost = £19,185 + £239,812 + £5,256,000 + £9,593 = £5,524,589

Present value of year 1 annual operation cost = £5,022,354, utilising the formula $\frac{F_t}{(1+d)^t}$

$Loan, L$ = Boiler capital cost + year 1 annual operation cost = £5,612,191

Applying Equation 6-10

Equal annual Loan repayment, C_{Lr} = £726,804

D.4 SC SS-ADIGT-CHP case annual cash flow model calculation (SSRP CHP)

$$\text{Initial cash flow, } F_0 = (5 \times 1.567\text{MW GT } + 1 \times 1.567\text{MW GT} - \text{CHP}) \times \text{capital cost per kW} + \text{cost of 1 boiler}$$

$$F_0 = (6 \times 1567\text{kW}) \times \frac{1000£}{\text{kW}} + 547.515\text{kW} \times 80\ £/\text{kW} = £9{,}445{,}801$$

Loan, L = initial cash flow = £9,445,801

Applying Equation 6-10

Equal annual Loan repayment, C_{Lr} = £1,223,274 (commences in year (3)

Year 1 annual net cash flow of SC SS-ADIGT-CHP case for SSRP:

$$\mathrm{C_{o/m}} = \text{total annual energy generated (kWh)} \times \text{O\&M cost per kWh}$$

$$= (\text{annual electricity generated (kWhe)} + \text{annual steam generated (kWht)}) \times \text{O\&M cost per kWh}$$

$$= (\text{annual electricity generated kWhe} + \text{CHP steam generated kWhth}) \times \text{O\&M variable cost per kWh} + \text{Boiler steam generated kWhth} \times \text{O\&M cost per kWh} + \text{CHP fixed O\&M cost}$$

$$= (239811.57)\ \text{kWh x } 0.004£/\text{kWh} + (80305139.13 + 25150263.37)\text{kWh} \times \frac{0.01£}{\text{kWh}} + 47010 = £1{,}102{,}523$$

$$\mathrm{C_f} = \text{total annual power generated (kWh)} \times \text{fuel price per kWh}$$

$$= (80305139.13)\text{kWh} \times 0.05£/\text{kWh} = £4{,}015{,}257$$

$$\mathrm{C_{Ge}} = \text{annual grid electricity consumption (kWhe)} \times \text{electricity tariff per kWhe}$$

$$= 2628000\text{kWhe} \times 0.1£/\text{kWhe} = £262{,}800$$

$$\mathrm{C_{Bh}} = \text{annual heat generated in boiler(kWht)} \times \text{gas oil price per kWht}$$

$$= 239812\text{kWht} \times 0.05£/\text{kWht} = £11{,}991$$

$$\mathrm{C_{emtx}} = (\text{annual total ADIGT emissions })\text{kg} \times \text{emission tax rate per kg} + \text{Boiler emission cost}$$

$$= (111502252.19)\text{kg} \times 0.005£/\text{kg} = £557{,}991$$

$$\mathrm{C_e} = \text{annual electricity consumption from CHP (kWhe)} \times \text{electricity tariff per kWhe}$$

$$= 49932000\ \text{kWhe} \times 0.1£/\text{kWhe} = £4{,}993{,}200$$

$$\mathrm{C_h} = \text{annual heat consumption from CHP(kWht)} \times \text{gas oil price per kWht}$$

$$= 4556419.83\ \text{kWht} \times 0.05£/\text{kWht} = £227{,}821$$

$$\mathrm{R_e} = \text{annual electricity exported (kWhe)} \times \text{electricity export tariff per kWhe}$$

$$= 30373139.13\text{kWhe} \times 0.05£/\text{kWhe} = £1{,}518{,}657$$

$$\mathrm{R_h} = \text{annual steam exported (kWht)} \times \text{gas oil price per kWht}$$

$$= 20593843.54\text{kWht} \times \frac{0.025£}{\text{kWht}} = £514{,}846$$

$$\text{Year 1 annual net cash flow, } \mathrm{F_1} = \mathrm{C_e} + \mathrm{C_h} + \mathrm{R_e} + \mathrm{R_h} - \mathrm{C_{0/m}} - \mathrm{C_f} - \mathrm{C_{Bh}} - \mathrm{C_{Ge}} - \mathrm{C_{emtx}}$$

$$= 4{,}993{,}200 + 227{,}821 + 1{,}518{,}657 + 514{,}846 - 1{,}102{,}523 - 4{,}015{,}257 - 11{,}991 - 262{,}800 - 557{,}991 = £1{,}303{,}962$$

$$\text{Present value of year 1 annual net cash flow } = \frac{\mathrm{F_1}}{(1 + \mathrm{d})^1}$$

$$\text{Present value of year 1 annual net cash flow } = \frac{1303962}{(1 + 0.1)^1}$$

$$\text{Present value of year 1 annual net cash flow } = £1{,}185{,}420$$

D.4.1 Simple payback period for SC SS-ADIGT-CHP case of SSRP:

$$\mathrm{SPBP_{SC\_CHP}} = \frac{\text{initial cash flow of SC ADIGTCHP case}}{\text{conventional case annual running cost} - \text{SC ADIGTCHP case annual running cost}}$$

$$\mathrm{SPBP_{SC\_CHP}} = \frac{9{,}445{,}801}{5022354 - 3560962} = 6.5\ \text{years}$$

D.4.2 Net present value for SC SS-ADIGT-CHP case of SSRP:

$$\mathrm{NPV_{SC\_CHP}} = \text{Total life cycle present value} - \text{initial cash flow of SC ADIGTCHP}$$

$$\mathrm{NPV_{SC\_CHP}} = 12{,}340{,}854 - 9{,}445{,}801 = £2{,}895{,}053$$

D.4.3 Simple payback period for RC SS-ADIGT-CHP case of SSRP:

$$\mathrm{SPBP_{RC\_CHP}} = \frac{\text{initial cash flow of RC ADIGTCHP case}}{\text{conventional case annual running cost} - \text{RC ADIGTCHP case annual running cost}}$$

$$\mathrm{SPBP_{RC\_CHP}} = \frac{9{,}492{,}811}{5{,}022{,}354 - 3{,}469{,}967} = 6.1 \text{ years}$$

D.4.4 Net present value for RC SS-ADIGT-CHP case of SSRP:

$$\mathrm{NPV_{RC\_CHP}} = \text{Total life cycle present value} - \text{initial cash flow of RC ADIGTCHP}$$

$$\mathrm{NPV_{RC\_CHP}} = 13{,}451{,}327 - 9{,}492{,}811 = £3{,}958{,}516$$

D.4.5 Simple payback period for ICR SS-ADIGT-CHP case of SSRP

$$\mathrm{SPBP_{ICR\_CHP}} = \frac{\text{initial cash flow of ICR ADIGTCHP case}}{\text{conventional case running cost} - \text{ICR ADIGTCHP case running cost}}$$

$$\mathrm{SPBP_{ICR\_CHP}} = \frac{9{,}539{,}821}{5{,}022{,}354 - 3{,}514{,}107} = 6.3 \text{ years}$$

D.4.6 Net present value for ICR SS-ADIGT-CHP case of SSRP:

$$\mathrm{NPV_{ICR\_CHP}} = \text{Total life cycle present value} - \text{initial cash flow of ICR ADIGTCHP}$$

$$\mathrm{NPV_{ICR\_CHP}} = 12{,}705{,}779 - 9{,}539{,}821 = £3{,}165{,}958$$